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THE LINCOLN SILL

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ABSTRACT

The Lincoln sill extends from Squirrel Island, just off Boothbay Peninsula on the central part of the Maine coast, inland in a northerly direction for some 50 miles, with nearly continuous outcrops. The mineral composition of the sill is unusual, consisting of large dark-colored alkalic feldspars generally with euhedral to subhedral outlines set in a matrix of biotite, hornblende, and augite with minor feldspar and quartz. The sill is nearly vertical throughout most of its extent, and its structure is essentially concordant with regional trend lines. It has been suggested that the origin of the magma which produced this unusual rock type with the attendant unusual chemical composition is through hybridization. Late- or post-magmatic alterations, the intrusion of granitic material, and dynamic metamorphism superimposed on the original intrusive account for the rock in its present condition.

INTRODUCTION

The Lincoln sill extends for about 50 miles in a northerly direction from Squirrel Island, which lies off Boothbay Peninsula and some 40 miles east of Portland, Maine. Occurrences of the sill rock, a porphyritic syenite, had been previously noted in the vicinity of Burkettville, Boothbay, and on Squirrel Island. The present study has shown these occurrences to be connected. It is proposed to call this igneous body the Lincoln sill after Lincoln County, Maine, through which the sill outcrops for a considerable distance. This paper gives an account of the sill, which is unusual both in extent and in petrography. A tentative hypothesis for the origin of the rock composing the sill is proposed.

PREVIOUS INVESTIGATIONS

The sill was first studied by Bastin[1] in 1905, at its area of most prominent outcropping near Burkettville. The rock composing the sill was termed "prowersose" in accordance with the chemical classification system of Cross, Iddings, Pirsson, and Washington. This term "prowersose" was first applied to an igneous rock from Prowers County, Colorado, which falls into the C.I.P.W. system as III.5.2.2. Following Bastin's work, Miss Ogilvie[2] in 1907 reported the rock on the coast in the vicinity of Boothbay and on Squirrel Island. On the basis of chemical analyses Miss Ogilvie recognized four types: one corresponding to prowersose; one receiving the new name "lincolnose"[3]; a third which was called "metamonzonose"; and a fourth which was termed "meta-umptekose." Accompanying Miss Ogilvie's report is a map of the occurrence of the rock on the Boothbay quadrangle.

Since the Maine rock to which the name "prowersose" was applied differs considerably in mode from prowersose in its original locality and shows variations which have led to the application of other normative names in accordance with the chemical classification scheme, such normative terms are avoided in this discussion.

OCCURRENCE

In form of occurrence the intrusion is apparently a large sill. It is generally concordant with the structural trend lines of the area, which are nearly vertical throughout much of the region and trend in a general northeast-southwest direction.

Figure 1 shows the general location and extent of the sill. The total length is about 50 miles. The average width of the zone of outcrops is probably close to $\frac{1}{2}$ mile. The maximum width (thickness) occurs in the originally described locality (Burkettville–South Liberty) where it attains a thickness of about $2\frac{3}{4}$ miles. Nowhere, except in this original locality, is the sill exposed over its full

[1] E. S. Bastin, "Some Unusual Rocks from Maine," *Jour. Geol.*, Vol. XIV (1906), pp. 173–80.

[2] I. H. Ogilvie, "A Contribution to the Geology of Southern Maine," *Annals N.Y. Acad. Sci.*, Vol. XVII (1907), pp. 519–58.

[3] The term "lincolnose" was rejected by Washington in *U.S. Geol. Surv. Prof. Paper 99* (1917), p. 35, since this subrang had already received the name "auruncose."

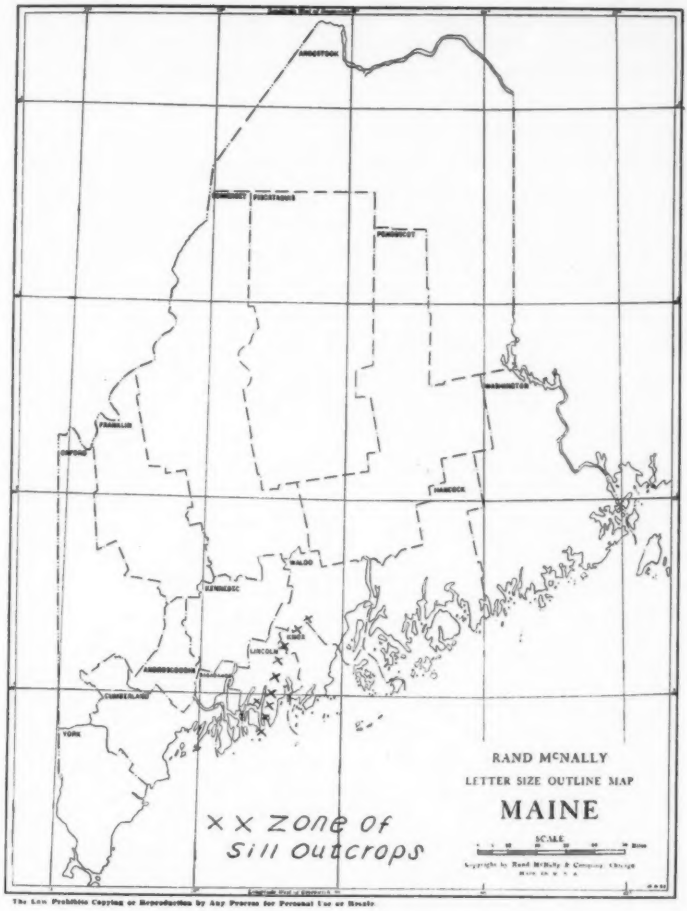

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FIG. 1.—Location and extent of the Lincoln Sill

width owing to the large amounts of granite and pegmatite which have intruded it. The large mass occurring south of Campbell Ponds, Boothbay quadrangle, however, achieves a width of nearly ½ mile. The sill pinches and swells along its course so that there are local variations in its thickness.

Areal distribution.—As shown on the key map (Fig. 1) the sill has been traced for some 50 miles. It outcrops from the extreme western edge of the Belfast quadrangle, east of Montville village, diagonally southwestward across the Liberty, Waldoboro, Wiscasset, and Boothbay topographic sheets. On the Boothbay quadrangle there are two separate occurrences of the rock comprising the sill. One, extending from Squirrel Island through Spruce Point and Mount Pisgah, connects with the well-exposed outcrops just west of Dodge Lower Cove. The other, or western occurrence, outcrops from the tip of the point just east of Townsend Gut northward as far as Campbell Ponds. These separate outcrops in the Boothbay region may be due to folding or faulting, or may be separately intruded sills. In any event, the rock comprising the two series of outcrops undoubtedly came from the same source.

Topographic expression.—In the South Liberty area, where the sill rock outcrops widely, a knobby surface has resulted from preglacial weathering and glacial scour. Jointing, more or less parallel to the surface configuration, has given many of these knobs a cap of detached or semidetached rock.

Miss Ogilvie[4] reported that the more massive syenite which comprises the central part of the sill in the southern exposures weathers more rapidly than more schistose phases which are found along the borders. This results in the formation of ridges and valleys, according to her interpretation. It seems likely, however, that the presence of granite in the more schistose phases gives it strength to resist the erosive processes.

Throughout the rest of the area of outcrop the syenite may be said to have no topographic expression of its own. Where it occurs on hills, the elevation or relief is due chiefly to the presence of granite or pegmatite that has intruded it; where it occurs in lowlands, the topography is probably due to the accidents of erosion rather than

[4] *Op. cit.*, pp. 537–38.

to any inherent weakness of the rock, since it makes up but a small percentage of the surface over which it outcrops. The overlying glacial drift is generally thin.

RELATIONSHIPS OF THE SILL

The Lincoln sill is intruded into a country rock of schist and gneiss. In the northern part of the area, at least, this is the Knox gneiss of Perkins and Smith.[5] The appearance of the gneiss may be decidedly igneous in hand specimen. In its broader field relations, its continuity of banding, and its structure this country rock has the indications of being an altered sediment. This character is evident throughout most of the area, particularly so in the southern and northern portions. Miss Bascom[6] tentatively placed the age of the schist in the Boothbay district as pre-Cambrian. Perkins and Smith are inclined to a pre-Cambrian age for their Knox gneiss in the northern part of the Liberty quadrangle, though they recognize the possibility that it may be the equivalent of the Penobscot formation of Bastin,[7] which was considered to be of Cambrian (?) age. Perkins and Smith,[8] however, are inclined to consider the Penobscot formation as of pre-Cambrian age. In the western and northern parts of the main exposures the syenite of the sill becomes fine grained and is in contact with a dense quartzitic rock, a hornfels undoubtedly developed by the intrusion.

Locally there are inclusions of a fine-grained grayish biotite gneiss, into which large phenocrysts of the blue feldspar characteristic of the syenite may protrude, giving the impression that the inclusion must have been softened somewhat in the syenite magma. The feldspars in places tend to orient themselves around the inclusions (Fig. 2). The long dimensions of the inclusions are in general parallel to the schistosity of the sill rock. The foliation of the schists dips locally at slight angles beneath the sill. The strikes of the

[5] E. H. Perkins and E. S. C. Smith, "Contributions to the Geology of Maine, No. 1: A Geological Section from the Kennebec River to Penobscot Bay," *Amer. Jour. Sci.*, Vol. IX (5th ser., 1925), p. 225.

[6] Florence Bascom, "On Some Dikes in the Vicinity of John's Bay, Maine," *Amer. Geol.*, Vol. XXIII (1899), p. 277.

[7] E. S. Bastin, "Rockland Folio," *U.S. Geol. Surv. Folio 158* (1908), p. 9.

[8] *Op. cit.*, p. 228.

schistosity of the country rock and of the foliation of the sill rock are concordant throughout the major portion of the area mapped, which probably indicates that the intrusion took place within mobile surroundings. A good locality showing the sedimentary character of the schists and actuality of the dips beneath the sill rock is in the Liberty quadrangle along the road southwest from Lucas Corner.

At the northern end of the sill the rock bordering the western margin is a much-crumpled sericite schist. This formation is

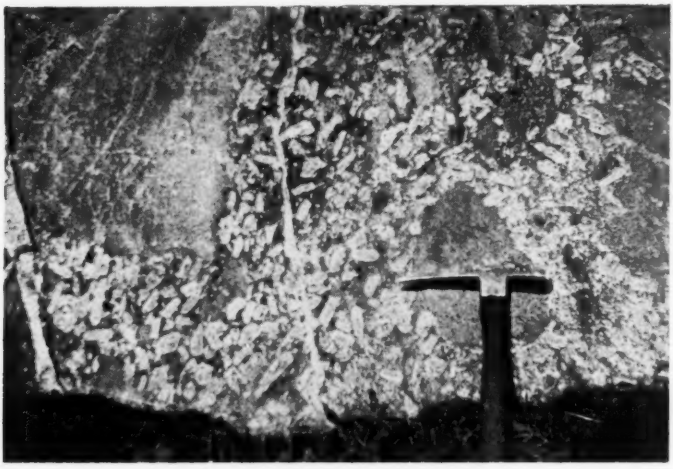

FIG. 2.—Inclusions in the syenite

beautifully exposed on Haystack Mountain, just north of Liberty village. It is the Hogback schist (pre-Cambrian?) of Perkins and Smith.[9] Arthur Keith has mapped this as of pre-Cambrian age on the preliminary geologic map of Maine issued in 1933. On the east side of the sill in the north, and apparently on both sides of the sill farther south, is another schist, not so crumpled but much granitized. This is probably to be correlated with the Knox gneiss of Perkins and Smith and the Penobscot formation of Bastin. It is possible that the Hogback schist is also a correlative of the Penobscot, being a less competent member. The author is inclined to the view that the Hogback schist is older and that more than one period of defor-

[9] *Ibid.*, p. 224.

mation is recorded in it. In the southern part of the area the Knox gneiss (?) becomes in places more quartzitic. The syenite of the Lincoln sill is the next younger rock of the region, with the possible exception of some of the basic dikes of local distribution. Intruded into the syenite is a medium- to fine-grained granite gneiss, pinkish on broken surfaces. The foliation is in general parallel to that of the syenite, but local divergences amounting to 10°–15° are present. Intruded into both of the preceding, and the country schists and gneisses as well, is a white pegmatitic granite. Locally this is folded with the syenite and forms lit-par-lit injections into the gneiss just mentioned. There is the possibility that there are two separate intrusions of pegmatitic granite, as indicated by the presence of stringers of this material that are folded and crumpled in close proximity to stringers that are not so deformed. Locally, in the area under discussion, there is another granite, gray, medium grained, and probably closely related to the pegmatite which cuts it. This granite is but slightly foliated, and the foliation is presumably a primary flow structure. There is also a coarse reddish- to dark-colored porphyritic granite cut by the pegmatite and not by the granite gneiss. This is not found in contact with the syenite in the northern part of the sill, but it cuts it in the southern and central parts. The latest intrusions of the area are the basic dikes, also for the most part parallel to the regional structures. In part these may be older than the pegmatite, but the majority are more recent.

Any definite statement as to the age of the Lincoln intrusive is avoided. Until more details of the geology are known, such statements are at best mere surmises. The author's present view is that the sill was intruded in Devonian time. The pegmatites and associated granites are quite well established as of that age.[10] If this view is correct, it follows that the movements of late Devonian time were the last important orogenic disturbances that affected this part of Maine.

PETROGRAPHY

Bastin and Ogilvie have described phases of the rock comprising the sill. Bastin[11] recognized two types, a coarse massive phase and a coarse foliated phase, both with essentially similar mineralogy. In

[10] E. S. Bastin, "Rockland Folio," *op. cit.*, p. 7.

[11] "Some Unusual Rocks from Maine," *op. cit.*, pp. 173–77.

the groundmass he recognized biotite, hornblende, titanite, apatite, quartz, titaniferous magnetite, and feldspar in decreasing order of abundance. The phenocrysts, which he estimated to constitute 41.5 per cent of the rock, he described as "perthitic intergrowths or a somewhat irregular penetration of orthoclase or microcline, and albite," with potassic feldspar predominating. He ascribed the feldspar zoning to slight variations in the bands, some of which are much richer than others in inclusions, and further noted that there is no progressive change in the composition of the feldspars from center to periphery. The bands of inclusions in the feldspars he believed due to cracking of the phenocrysts and introduction of the still fluid groundmass material. In addition to these features mentioned by Bastin, Miss Ogilvie[12] noted an abundance of pyroxene in some of her slides. On the basis of chemical analyses she subdivided the rock into several normative subrangs. Both Bastin and Ogilvie report similar accessory minerals—namely, apatite, zircon, rutile, and magnetite.

The present investigation shows that four general types of the rock may be recognized throughout the area of outcrops. These are: (1) normal, coarse-grained, porphyritic, massive phase; (2) border phase of medium- to fine-grained, massive, nonporphyritic type; (3) schistose phases of the two preceding types; (4) a granitized type.

1. *Coarse-grained, massive, porphyritic type.*—In its typical and most readily recognizable form the rock of this sill is a coarse-grained porphyritic syenite with large phenocrysts of dark-colored feldspar and a groundmass of biotite and hornblende with subordinate feldspar. The phenocrysts reach an observed maximum of $3\frac{1}{4}$ inches in length. They are typically euhedral to subhedral and generally twinned on the Carlsbad law. They frequently contain cracks filled with groundmass material. Orthoclase dominates with, however, much microcline, or perthite, in combinations. Characteristically, these phenocrysts are crowded with minute inclusions, many of which are brownish globules of indeterminate composition, possibly rutile. There are also swarms of minute greenish needles, sometimes oriented parallel with the cleavage, sometimes at random. Much of the minute rod material may be of hornblendic nature; some may be

[12] *Op. cit.*, pp. 536–42.

biotite fibers. This type of inclusion suggests pneumatolytic alteration of the feldspars. Larger inclusions, consisting of biotite, augite, and hornblende, are often present, as noted by Bastin. In many cases these parallel the crystal outlines and zoning. This suggests that the feldspar was crystallizing at the same time as the groundmass, with the zonally arranged inclusions representing halts in the crystallization of the phenocrysts.

The phenocrysts are megascopically zoned. The zoning seems to be due in part to the differences in the numbers of the minute inclusions in the different zones, which may indicate that the zones are of slightly different composition. Another type of zoning, common and best developed in the schistose types, is due to localization of a perthitic type of intergrowth (Fig. 5).

Augite and hornblende are abundant in the groundmass, with frequent euhedral and subhedral outlines. The augite shows stages of alteration to hornblende, and much of the hornblende may be a secondary product. It, in turn, is altering to biotite. The biotite is probably of two generations—one the result of alteration, the other original from the crystallization of the magma. Magnetite, and frequently titanite and rutile, are associated with the biotite. A curious occurrence noted is a wormlike appearance of the biotite at its margins, similar to vermicular quartz growths but here consisting of biotite and feldspar.

Plagioclase is sparingly present in the groundmass, generally with the composition of acid andesine. Orthoclase is particularly abundant in the finer-grained types. Quartz is very sparingly present in the groundmass and appears to be the last mineral crystallized. Apatite is an abundant accessory mineral, present in euhedral crystals and as inclusions in all the other constituents. Titanite, rutile, and magnetite are abundant, usually associated with the biotite.

The texture of this type is generally porphyritic-granitic, and the rock is classified as a porphyritic syenite or alkali syenite. Mineral alterations suggest that hydrothermal or pneumatolytic metamorphism has played an important part in forming the final product.

2. *Medium- to fine-grained, massive, nonporphyritic type.*—This type is limited to contacts with the country rock and is most widely

exposed in the northwestern part of the lenslike enlargement of the intrusion where it is in contact with a hornfels. It grades into the coarse porphyritic phase toward the interior of the mass.

This type, lacking in phenocrysts, has an even granular texture and is composed of feldspar and dark minerals in about equal parts. Biotite is the most common dark mineral, with hornblende occasional. Many of the feldspars are hypidiomorphic and show Carlsbad twinning. The texture is finer, and the rock is darker toward the contact with the country rock.

The orthoclase is similar to that of the normal coarse phase. Augite occurs, in many instances altering to uralite. Biotite is generally present, associated with augite and hornblende. The accessory minerals are magnetite, apatite, titanite, and rutile. One of the chief differences between this type and the coarse massive type, beside grain size, appears to be in the greater amount of plagioclase in the border phases. It varies from basic to acid andesine. Sericite is also more abundant, possibly owing to contact assimilation of sericite schist. In general, there appears to be a gradation from alkali syenite to syenite and monzonite toward the margins of the sill, locally approaching a diorite or augite diorite at the contacts.

3. *Schistose, foliated, locally crushed type.*—The massive types give way in some places to foliated phases in which the feldspar phenocrysts are distinctly alined, and the groundmass materials show parallelism. This is the most widely outcropping type, occurring throughout the mass both at the margins and in the interior. The same minerals are present as in the massive phases. A certain amount of secondary mica forms a tightly adhering skin about the phenocrysts. The rock of this type varies from coarse porphyritic to even granular schists of medium texture. In some of the schists the feldspars are crushed, changing the color from dark to light. Commonly the borders of the phenocrysts are crushed, leaving uncrushed bluish cores. Many of the phenocrysts are lenticular. Some of the mica indicates differential movement within the mass after consolidation.

Much of the foliated structure is ascribed to magmatic flow and is eutaxitic, for the divergence of the schistosity from the regional

trends is in places pronounced and could not be accounted for as the result of deformation in the solid state. Both flow structure acquired in emplacement and schistosity developed by post-magmatic deformation are held to be present.

The feldspars show the same characteristics as in the massive types and are crowded with minute globular and rodlike inclusions. Similar zoning is present in the phenocrysts. The minerals whose presence and arrangement give the rock its foliation are biotite and hornblende. The biotite shows alteration to titanite and magnetite, localized at the edges of the biotite and along cleavages (Fig. 3). The hornblende is partly uralitic and is altering to biotite. In this type there is very little pyroxene.

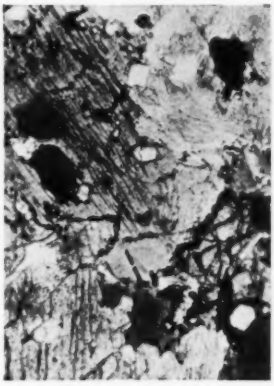

FIG. 3.—Alteration of biotite. ×15. Plain light.

4. *Foliated type, with material introduced.*—This type, like the preceding, shows a decided foliation and variations in grain size, from coarse to medium. In the porphyritic, coarser-textured type the blue feldspar phenocrysts have often acted as localizers for introduced material, and about them frequently are rims of feldspathic material with free quartz (Fig. 4). In the finer-grained types the rock may have a decidedly granitic appearance. The fact that stringers of the introduced material can, in places, be traced through the rock into larger dikelets shows that the material is actually introduced and does not result from the mere crushing of the feldspars. This type is found here and there throughout the length of the sill.

The phenocrysts are dominantly microcline and orthoclase, with considerable intergrowth of perthitic albite. Inclusions similar to those previously described are present. The groundmass is chiefly biotite and hornblende, with minor andesine feldspar and quartz. The accessory minerals are those characteristic of the sill throughout. The zoning in the feldspars appears to be due in part to the concentration of the perthitic intergrowths in certain zones. The pho-

tomicrograph (Fig. 5) illustrates this type of zoning. Curious saw-tooth patches of quartz appear in some of the slides (Fig. 6). The saw-tooth edge is related to the twinning of the feldspar with which it is associated. Sederholm[13] has figured such saw-tooth patches, which he ascribes to contemporaneous crystallization of the saw-tooth patch and the containing feldspar. This is, of course, a possible explanation. Since, however, these curious patches appear

FIG. 4.—Syenite intruded by stringers of granitic material. Approximately one-third actual size.

to be confined to the types that show definitely later added material, it appears more probable to the writer that they represent replacement. The quartz present in the groundmass appears to be the latest material to have crystallized.

STRUCTURE

GENERAL STATEMENT

The area under consideration is characterized in the northern part by close folding; in the southern part the folding is less close,

[13] J. J. Sederholm, "On Synantetic Minerals and Related Phenomena," *Bull. Geol. de Finland, No. 48* (1916), Fig. 38, Pl. VII.

with gentle to moderate dips. The strike is prevailingly N. 30°–40° E., in the northern part, swinging in an arc convex to the northwest, so that in the southern part the strikes are nearly north-south. Northeast of Campbell Ponds (Boothbay sheet) over a distance of 8–10 miles the dips are much less steep than is general for the more northerly and southerly portions, ranging here from 15° to 25°. Pegmatite is widely outcropping over this part. There is no reason to suspect overturning, and the structure may be domal, possibly owing to the intrusion of the granite-pegmatite mass.

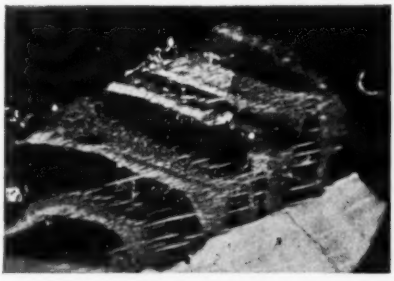

FIG. 5.—Perthitic zoning in feldspar. Crossed nicols. ×15.

FIG. 6.—"Sawtooth" quartz in plagioclase. Crossed nicols. ×45.

Throughout most of the area later intrusions of granite and pegmatite have engulfed the sill rock, leaving stringers which may be traced locally. The remnants are surprisingly numerous, however, and the general continuity of the sill from Squirrel Island to South Montville is clearly established. From a broad point of view, much of the sill may be considered as roof pendants of the later granite batholith. The lit-par-lit injections of granite into the sedimentary rocks and the granitization of the sediments and syenite substantiate the conclusion that only the upper portions of the batholith have been exposed.

STRUCTURE OF THE SILL

Foliation.—The foliation of the sill in general conforms closely to that of the enclosing schists and gneisses. Around the borders of the

principal northern outcrop the strike of the foliation parallels closely the contacts; also parallel to this foliation of the sill and to the contact is the structural trend of the country rock. As the sill intrusion here outcropping is broadly lens-shaped, the conformity of the country rock structure to the contact causes some local deviation from the regional trends which average N. 30°–40° E. This curvature of the strike of the country rock around the intrusion can be seen along the contact east of the road from Washington village to South Liberty village, along the Plains road from South Liberty to Fish Turn, and also at Lucas Corners. The contacts are nearly vertical but tend to dip slightly beneath the sill, as shown, for example, by a northwesterly dip just north of the campgrounds, Liberty sheet, and by the southeasterly dip just south of the South Liberty church. It is generally true that the borders of the intrusion show better-developed foliation than the interior parts. Some tendency toward foliation is shown in most parts of the mass, however, and this holds throughout the length of the sill. This foliation varies from a very crude schistosity, with faint alinement of the large feldspars, to well-developed fissility, where practically all the feldspars are alined parallel to this structure and are crushed to varying degrees.

In the interior of the northern lens the foliation changes direction rapidly and markedly. In the southern portion of this lens nearly east-west strikes prevail, while east of Muddy Pond the strike of the foliation is N. 25° W. This local variability of the strike of the foliation over a wide portion of the compass arc is noteworthy (Fig. 7). Throughout the rest of the area, extending from the southern end of this northern lens to the southwest for a distance of approximately 45 miles, the strike of the foliation, which is generally present, follows the regional structure closely. The dips of the foliation also closely conform to the dips of the regional structure which, for the most part, are close to vertical. The outcrop on the state highway west of Stickney's Corner shows this verticality nicely, and also shows the feldspars alined not only in the horizontal plane but in the vertical as well. The longest axes of the feldspars are for the most part vertical, with the intermediate axes parallel to the strike of the schistosity. Locally the sill departs markedly

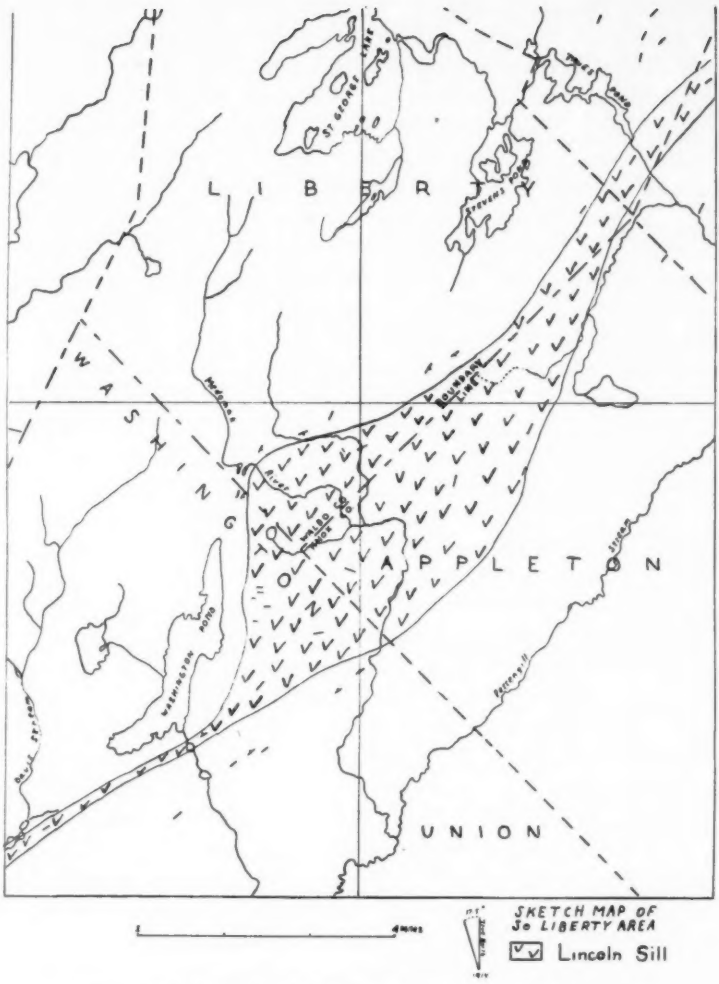

FIG. 7.—Sketch map showing structural trends in South Liberty area

from the vertical. Just south of Campbell Ponds, Boothbay quadrangle, for example, the dips are to the west, averaging for this series of outcrops about 50°–60°, steepening to the south. Again, the outcrops west of Dodge Lower Cove, Boothbay sheet, indicate gentle dips, about 15°–20°, steepening to the north. On the northern part of the Waldoboro sheet, nearly on the Knox-Lincoln county line, the foliation of the sill is nearly horizontal with a sill of granite intruding the syenite, as seen on a cliff face.

Jointing.—Jointing is not prominent in most of the sill. As already indicated, joints of recent origin are conspicuously present in the vicinity of Burkettville, Liberty quadrangle. These tend to follow surface configuration and to develop along the planes of schistosity where these are gently inclined. Joints of any other kind were not noted.

Shearing.—That the sill has been subjected to shearing is evidenced by the local crushing of the phenocrysts and the formation of augen. Locally the sill rock is somewhat crumpled, and at one locality in the northern part of the Waldoboro sheet some of the feldspars are decidedly bent. An *ausweichung* cleavage has been locally superimposed on the flow cleavage. A further evidence of shearing is found in the "skin" of biotite on the feldspar crystals in the sheared phases, as noted by Bastin.[14]

In the northern area of main outcropping, about 1 mile southeast of South Liberty village, a shear zone 20 feet in width, striking about N. 60° W., crosses the road. Along this shear zone localized weathering has reduced the syenite in part to granular material. Slickensides show some movement along this zone and point to a relative displacement of the northeast side upward and to the southeast, along nearly vertical planes. That this movement preceded the intrusion of the granite and pegmatite is shown by the intersection of the slickensides by dikes. This shear zone can be traced for a few hundred yards; it is lost under the mantle rock and glacial drift.

Dikes cutting the sill.—These dikes consist chiefly of pegmatite, aplite, and the associated white granite. Most of these, constituting the great bulk of granitic material intruded into the sill, are injected parallel to the foliation of the host. These vary in magnitude from

[14] "Some Unusual Rocks from Maine," *op. cit.*, p. 177.

minute threads, intimately intruded, to clean-cut dikes often of considerable size. Such dikes ordinarily stand up several inches above the sill rock, owing to their superior resistance to weathering. It is to the presence of such ribbing that many of the hills, made up in part of the syenite, owe their relief. Examples are Bodge and Haskell hills on the Waldoboro quadrangle. This type of intrusion is definitely later than the magmatic stage of the sill; how much later is, of course, a question. Locally there are cross-cutting dikes, some of which make an angle of 90° with the foliation. These may follow joints developed during or shortly after crystallization.

Drag folds in the sill.—Locally, drag folds of the granite and pegmatite dikes indicate the relative movements within the sill and country rock as well. It is apparent, therefore, that deformation of the region continued during the intrusion of part of the granite. Undeformed granites and related pegmatites indicate that this intrusion probably took place in the waning stages of this diastrophism and probably continued after diastrophic movements had ceased.

Summary of structure.—Enough evidence has been cited to show that the foliation of the sill rock is in part an original flow structure and in part a secondary result of metamorphism. That the deformation continued after the intrusion of the sill is evidenced by the structural features of shearing, drag folds, and the development locally of *ausweichung* cleavage. Further, the continued deformation of subsequent intrusions has been indicated. By the interpretation of the Cloos school it is thought that the intrusion of the sill in the main was from far below, with considerable horizontal movement of the magma along the length of the sill—presumably the result of accompanying deformation. By means of structural details local structure can be worked out. For example, along the Plains road from South Liberty to West Appleton, Liberty quadrangle, drags indicate that the easterly gneissic beds moved south and up relative to the westerly beds. This would indicate that the rocks here constitute the southeast limb of an anticline. Other details could be cited. It is clearly recognized, however, that drag folds, particularly minor drags, may be misleading, and not until the stratigraphy and structure of the region as a whole have been worked out can any

generalizations be valid. The general parallelism of foliation and bedding, the intimate intrusion with the formation of much injection gneiss, and the apparent complexity of the structure render such work difficult in the extreme. With the recognition that much of the gneiss is partly sedimentary and amenable to stratigraphic methods, it is thought that close attention to the minor structures, consideration of the different responses to metamorphic environments of different types of materials—together with their relations to the

TABLE 1

CHEMICAL ANALYSES OF THE LINCOLN SILL

	1*		2†		3‡		4§		AVERAGE BASALT FOR THE REGION
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	
SiO_2	52.26	52.59	55.17	54.14	58.74	59.99	59.64	58.51	47.37
Al_2O_3	10.63	17.22	18.01	17.38	14.71	15.73	14.76	17.84	16.53
Fe_2O_3	2.47	1.72	0.08	1.66	0.48	0.99	0.41	1.10	2.69
FeO	5.45	5.06	5.41	4.81	3.70	2.92	3.57	3.24	7.90
MgO	9.32	5.36	5.29	5.20	5.47	3.10	5.53	3.44	8.38
CaO	5.62	7.74	5.64	7.50	3.34	4.48	3.17	4.96	12.10
Na_2O	1.60	1.64	2.12	2.19	5.70	5.71	3.27	3.26	2.70
K_2O	5.99	5.95	5.48	5.44	3.79	3.75	6.69	6.94	0.33
TiO_2	1.92	0.89	2.33	0.86	1.87	0.51	2.11	0.57	1.39
P_2O_5	0.98	.....	0.25	.....	1.00	.....	0.60	.....	.....

* 1*a*, "prowersose"; 1*b*, 64 per cent basalt, 34 per cent orthoclase, 2 per cent albite.
† 2*a*, "lincolnose"; 2*b*, 62 per cent basalt, 31 per cent orthoclase, 7 per cent albite.
‡ 3*a*, "meta-umptekose"; 3*b*, 37 per cent basalt, 21.5 per cent orthoclase, 41.5 per cent albite.
§ 4*a*, "meta-monsonose"; 4*b*, 41 per cent basalt, 39 per cent orthoclase, 20 per cent albite.

several intrusions and the possible localization of orogenies that have affected the area—and detailed lithologic studies will permit the working-out of much information concerning the region.

CHEMICAL NATURE OF THE ROCK

The chemical analyses available for this rock are presented in Table 1 for purposes of easy comparison. No new analyses are presented. High potash, high magnesia, low lime, low ferric iron, and high ferrous iron are outstanding characteristics. There are also noteworthy amounts of titania. The analyses from the southern part of the sill, presented by Miss Ogilvie, differ somewhat from the one presented by Bastin as representing the northern occurrence.

This difference consists notably in the higher alkali–lower alumina content shown by Bastin's analysis. Only the groundmass of one of the specimens analyzed for Miss Ogilvie corresponds with the analysis given by Bastin. The analyses of the other specimens taken by her show variations in composition sufficient to fall into separate pigeonholes of the chemical classification of Cross, Iddings, Pirsson, and Washington.

Miss Ogilvie states her conclusions as to the group as a whole:

> This group of rocks presents similarities to the shonkonites, yogoites, and monzonites of the Bearpaw and Little Belt Mountains, and with the prowersose of Two Buttes, Colorado. It also has affinities with the ciminites and vulsinites of Italy. It has no close allies at hand, except the prowersose described by Bastin which is probably part of the same rock body.
>
> The similarity with the distant rocks is chemical only. The other types are unmetamorphic and in some cases surface volcanics. The Maine rocks are evidently of deep-seated origin, and highly metamorphic, the resulting mineralogy and structure departing widely from those of allied types. The mode departs widely from the norm for the same reason, namely that the minerals actually present are in large part the result of dynamic processes, and are in general those of higher specific gravity than the normative ones.[15]

Consideration of chemical data.—A variation diagram (Fig. 8) has been constructed plotting silica percentages on the abscissa and percentages of the other oxides on the ordinate. This shows graphically the composition of the rock series from the vicinity of Boothbay, Maine, and also the composition of a series somewhat similar chemically. The latter series, from Yogo Peak, Montana, has been interpreted by Weed and Pirsson[16] from field evidence to result from differentiation of a parent-magma. They back up their argument by mineralogical and chemical data. Miss Ogilvie evidently considered the Boothbay rocks to have been derived from a common parent-magma for she states: "It is evident that there is a regular progression in chemical characters from I to IX."[17] The curves on the variation diagram, however, do not indicate any simple relationship. Indeed, in view of the irregularity of the curves shown on the

[15] *Op. cit.*, p. 543.

[16] W. H. Weed and L. V. Pirsson, "Igneous Rocks of Yogo Peak, Montana," *Amer. Jour. Sci.*, Vol. L (3d ser., 1895), pp. 467–79.

[17] *Op. cit.*, p. 555.

diagram, it seems improbable that such a relation exists. It may well be that two differentiation series are represented in the analyses given by Miss Ogilvie and the products of differentiation complicated by hybridism and metamorphism.

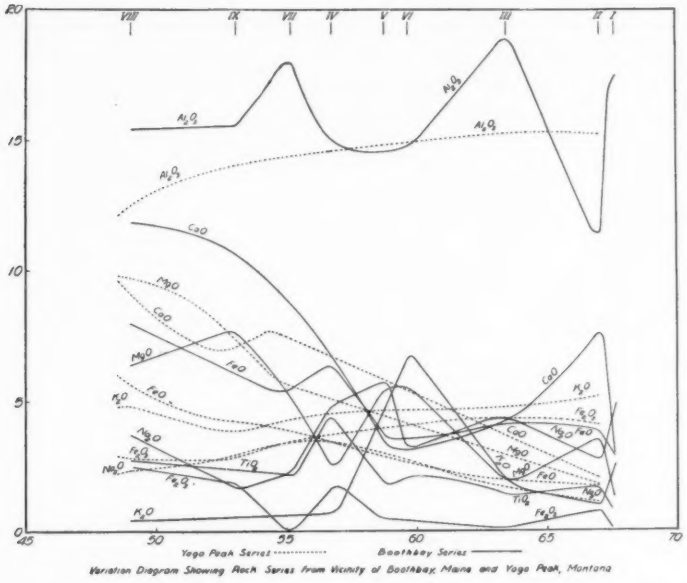

FIG. 8.—Variation diagram showing composition of Boothbay series and Yogo Peak series.

In her final paragraph on "Metamorphism" Miss Ogilvie states:

> Since unaltered dikes and metamorphic masses are clearly derived from the same magma, it becomes possible to estimate the kind and amount of alteration that has taken place in the metamorphic types. . . . . The conception of metamorphism here entertained is that of alteration without addition or subtraction of material. . . . . In the region discussed there is no reason for suspecting any changes in chemical composition, and it is believed that the quantitative system furnishes the most logical method of regarding them.[18]

This position is regarded as untenable by the writer. In the first place, it remains to be shown that the rocks of this series are derived

[18] *Ibid.*, p. 558.

from the same magma. Further, migmatites are certainly present in the region. Finally, it may be doubted if significant metamorphism takes place without significant change in composition of the rock affected, except in instances of metamorphism brought about by purely thermal effects.

The variation diagram of the Lincoln-sill analyses is instructive (Fig. 9). The percentages of silica are plotted on the abscissa and the percentages of the other oxides on the ordinate. It is to be noted that the curves for CaO, FeO, Fe_2O_3, P_2O_5, and TiO_2 are quite regular smooth curves, whereas the curves for Al_2O_3, K_2O, and Na_2O are apparently abnormal for a series of related rocks. This suggests that orthoclase and albite may be variable constituents. As can be seen from the variation diagram of the analyses of the Boothbay rocks, the sill rocks do not seem to fit into a scheme of differentiation accounting for the whole series of igneous and metamorphic rocks of the region. The variation curves do show, however, that the sill rocks are closely related throughout their extent, so far as analyses are available.

A study of the chemical analyses, as plotted on the diagram, suggests that a combination of the basaltic types and varying proportions of albite and orthoclase might yield synthetic analyses comparable with the actual analyses of the sill types. Such a comparison was attempted, using the average basalt for the region and solving the problem graphically, to determine the amounts of feldspar necessary to produce analyses similar to the analyses of the sill. The degree of success with which this comparison met is shown in the accompanying table (Table 1). It will be noted that in each case the following general statements appear to be valid:

1. There is a general tendency to give an excess of alumina.
2. There tends to be a slight deficiency of FeO.
3. There tends to be a slight excess of Fe_2O_3.
4. There tends to be a deficiency of MgO.
5. There tends to be a deficiency of TiO_2.
6. There tends to be an excess of CaO.

The same differences are present in the case of the Knox County analysis but in an accentuated degree. The material for that analysis was not fresh. From this constant tendency toward excess

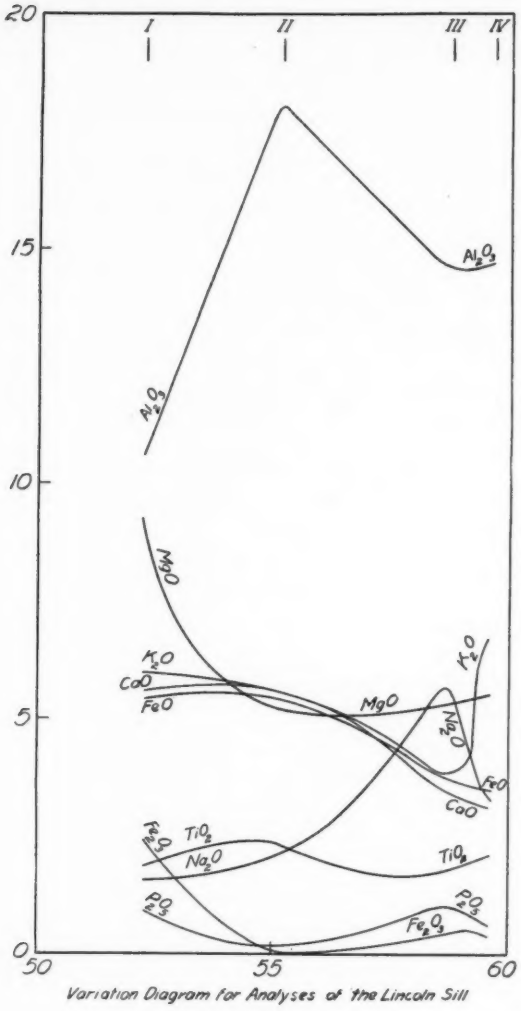

FIG. 9.—Variation diagram of the sill rock

or deficiency it appears that the average basalt used in the comparison was somewhat too calcic, with too little magnesia and with a slight excess of ferric iron and a deficiency of titania.

It is to be noted that the granite pegmatite of the region is high in potash and low in lime. The basalt taken as average for the region also deviates from the normal basalt in the direction to produce such a rock by combination with feldspathic materials. Other combinations, such as the schist of the region plus basalt, for example, gave results not at all comparable to the analyses of the Lincoln sill. The results of this comparison are not convincing; they are illuminating, however, to the extent that they show that a combination of basaltic rocks, similar to those present in the region, with varying amounts of orthoclase and albite would tend to produce a mixture of chemical composition similar to that shown by the analyses of the sill rock.

ORIGIN OF THE ROCK

Origin through differentiation.—Differentiation is undoubtedly the most important and generally applicable process producing igneous rock series of differing composition. If the sill rock is a product of differentiation, we are faced with the problem of determining from what it differentiated and by what mechanism. The observational fact that the coarse interior phases grade outward toward the margins into a finer-grained border phase seems to preclude either settling or rising of crystals. It is obvious that the rock crystallized from solution and that the mineral constituents grew essentially *in situ*. If this were not so, the feldspar phenocrysts would maintain their size clear to the margins. Phenocrysts are rare in the marginal facies and of much smaller size than those of the interior. The evidence here seems to indicate that the phenocrysts had not separated from the liquid at the time of intrusion.

One other mode of differentiation beside the settling and rising of crystals may be considered. When a crystal mush has formed, deformation may cause the interstitial liquid to drain out or be forced out through compaction of the meshwork. A difficulty here arises, in application of this process to the rocks in question, in accounting for the association of orthoclase crystals, composed of material which theoretically should have been squeezed out with the

liquid, or drained off, and set into a groundmass of material which, again theoretically, should have constituted the meshwork left behind. It is supposed that an especially dry magma favors an early crystallization of orthoclase and the production of such rocks as essexite; a larger tenor of water breaks up the orthoclase molecule and leads to the formation of mica and quartz, as found in diorite and granite.[19] That this is not the cause of the early formation of the orthoclase and microcline in this rock is shown by the presence of such minerals as biotite and hornblende which in part are considered as original constituents. This is a possibility, however, that should be kept in mind in considering the origin of this rock.

These considerations bring to mind the possibility that, instead of the conditions postulated above, we might conceive conditions under which feldspathic material may be introduced into a basic medium rather than being eliminated—a line of attack that has already been indicated in preceding paragraphs. The rocks comprising the sill seem to be a group apart, differing in essential characteristics from the other igneous and metamorphic rocks of the region; consequently, the origin appears to be an individual problem in itself, related to be sure to the history of the region but with such a combination of historical factors as to produce the unusual type to which we here refer.

Origin through hybridism.—True hybrid rocks are apparently rare. Harker[20] describes a notable occurrence in Skye which he interprets as a blending of gabbroid and granitic magmas. Clapp[21] describes a hybrid from Essex County, Massachusetts, resulting from the mixture of syenitic and diabasic magmas, and others from the same general locality. Winchell[22] in describing the orthoclase gabbro from Duluth, Minnesota, ascribes the rock to incorporation of wall rock by gabbroid magma. These are but a few of the instances that might

[19] A. N. Winchell, "Notes on Petrogeny" (unpublished manuscript).

[20] Alfred Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv. United Kingdom* (1904), pp. 181 ff.

[21] C. H. Clapp, "Geology of the Igneous Rocks of Essex County, Massachusetts," *U.S. Geol. Surv. Bull. 704* (1921), pp. 117 ff.

[22] A. N. Winchell, "Mineralogical and Petrographic Study of the Gabbroid Rocks of Minnesota," *Amer. Geol.*, Vol. XXVI (1900), pp. 285–96.

be cited in detail. A bibliography of the subject is given in Daly's *Igneous Rocks and the Depths of the Earth.*"[23]

The net effect of hybridization—that is, mixing of rock types in an intimate fashion, producing new types—appears to be in the direction of rendering the composition more nearly like the average igneous rock than either parent. This statement, in effect, is the principle shown by Leith and Mead[24] in their consideration of contact metamorphism. It is the tendency to be expected from the nature of the case. A basic rock is, perforce, more liable to alteration by acid magmas, and an acid rock more effectively altered by basic magmas, with the results in both cases tending to produce a rock of intermediate composition.

Straight-line diagrams have been drawn up to illustrate the changes taking place in basic rocks contact-metamorphosed by acid intrusions (Fig. 10). The changes taking place in hybridism appear to be of the same character but further advanced. Thus, while K_2O, for example, is generally introduced under contact conditions of an acid intrusion, the same tendency is more marked in the hybrid types. A straight-line diagram has also been constructed to show the comparison of the average basalt of the region with the sill rock types analyzed (Fig. 11). It is to be noted that the general tendency toward introduction or loss is similar in these diagrams. In other words, the pattern is essentially similar although the individual cases vary. This suggests that the process here hypothecated may have been operative—it does not prove but merely corroborates the possibility.

It is noteworthy that, in all the cases that have been taken under consideration here, the hybrid types have been porphyritic in texture. Why this should be so the writer is not in a position to state. In part it may be due to the fact that a hybrid magma resulting from a mixture is inoculated with crystals which naturally continue to grow.

[23] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., 1934), p. 300.

[24] C. K. Leith and W. J. Mead, *Metamorphic Geology* (New York: Henry Holt & Co., 1915), pp. 158–60.

Time and place of hybridism.—If we consider that the sill may possibly be made up of hybrid types, it may be well to consider when and where the mixture took place. The petrographic evidence points toward the mixture's having been produced before the emplacement of the sill in its present position. This is the evidence of the well-defined contacts and of the gradational textures toward the margins. It seems possible that the intrusion of a basaltic magma, not far different in composition from the average basalt of the region, was

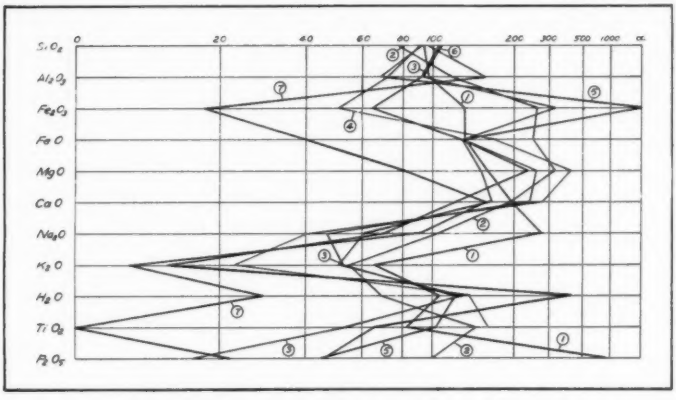

FIG. 10.—Straight-line diagram* showing the trends of alteration in contact and hybrid rocks. Each pair of analyses is numbered for identification.

1. Diabase: A. Bramhall and H. F. Harwood, "The Dartmoor Granites," *Quart. Jour. Geol. Soc. London*, Vol. LXXXVIII (1932), p. 234.

2. Gabbro diorite: C. H. Clapp, "Geology of the Igneous Rocks of Essex County, Massachusetts," *U.S. Geol. Surv. Bull. 704* (1921), Table of Analyses.

3. Gabbro diorite: C. H. Clapp, "Geology of the Igneous Rocks of Essex County, Massachusetts," *U.S. Geol. Surv. Bull. 704* (1921), Table of Analyses.

4. Greenstone: S. R. Nockolds, "The Dhoon (Isle of Man) Granite: A Study in Contamination," *Mineral. Mag.*, Vol. XXII (1931), p. 504.

5. Amphibolite: W. Lindgren, *Mineral Deposits* (New York, 1928), p. 760.

6. Diorite: *ibid.*

7. Anorthosite: F. F. Grout and W. W. Longley, "Relations of Anorthosite to Granite," *Jour. Geol.*, Vol. XLIII (1935), p. 135.

* For a description of this method of diagramming analyses see C. K. Leith and W. J. Mead. *Metamorphic Geology* (New York: Henry Holt & Co., 1915), pp. 288–90.

followed by emanations of a pegmatitic nature. In this connection it is well to refer again to the variation diagram. If the rock were the

result of a simple mixture of an acid and a basic magma, the composition of the sill should lie between the extremes with the variation curves approaching straight lines. Such evidence has been used by Gilluly[25] to substantiate his argument that a certain granite rich in albite has been formed from a quartz diorite by the effect of liquids approaching acid pegmatite in composition. In our computations of percentages of oxides comparable to the actual analyses of the sill by the addition of albite and orthoclase to the average basalt of the

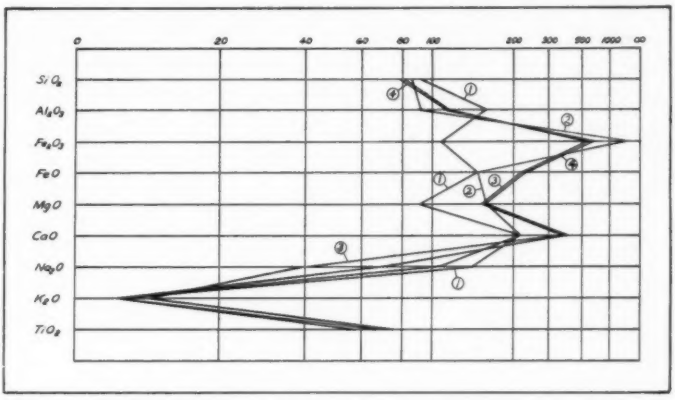

FIG. 11.—Straight-line diagram showing comparison of analyses of sill with average basalt of region. Each pair of analyses is numbered for identification.

1. Prowersose
2. Lincolnose
3. Meta-umptekose
4. Meta-monzonose

region, it is shown that the pegmatitic constituents necessary are not uniform. It would probably be exceptional if such pegmatitic materials were uniform over any considerable distances. Pirsson states of pegmatites: "Another characteristic is the extreme variability in the relative proportions of the component minerals from place to place. . . . ."[26] An alternative possibility to the one just suggested is that deep-seated assimilation of pegmatitic material by basic magma gave rise to the unusual rock type of the sill.

[25] James Gilluly, "Replacement Origin of the Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Prof. Paper 175C* (1933), pp. 74–76.

[26] L. V. Pirsson, *Rocks and Rock Minerals* (2d ed.; New York: J. Wiley & Sons, 1926), p. 180.

Late alterations.—The sill rock has to some extent been subjected to late- or post-magmatic alteration. The minute rods and globular inclusions of the feldspar phenocrysts are probably late. Where the feldspar is cracked and healed with later material, these tiny rods can frequently be seen to cross the fracture uninterruptedly. It seems probable that much of the minute inclusion matter is in the nature of a replacement and in this case probably indicates late emanations, presumably pneumatolytic, that penetrated through the rock. The alteration of the augite to hornblende, and the hornblende to biotite, may be a hydrothermal change related to magmatic emanations, as is probably the baueritization of the biotite with the production of abundant magnetite. The presence of small amounts of epidote among the alteration products of the augite also indicates hydrothermal alteration. Sericite is surprisingly rare, however.

In the types of the sill rock which clearly have had material introduced after primary crystallization had finished, there is evidence of replacement of the earlier minerals by later additions, especially the feldspars. The saw-toothed patches of quartz replacing plagioclase (Fig. 6) and the replacement of the orthoclase-microcline-albite phenocrysts by granitic aggregates, as collected on Squirrel Island, illustrate this. It is possible that some of the zonal intergrowths of perthite in the phenocrysts, also, may be due to replacement. The whole subject of the interpretation of myrmekitic and perthitic intergrowths is still open, but there is a growing tendency to regard such intergrowths as capable of explanation by more than one mode of development and to suppose that replacement is one method by which the texture is produced.

ACKNOWLEDGMENT.—The writer wishes to thank Dr. A. N. Winchell for suggestions during the course of the investigation and for critically reading the manuscript. Thanks are due to Dr. W. A. Tarr for helpful field discussion and to Drs. Tarr and Bastin for criticizing the manuscript. For invaluable assistance in the field and in preparation of the paper the writer is indebted to Helen B. Trefethen.

HETEROGENEITY OF PARENT MAGMA

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ABSTRACT

Processes of differentiation are commonly considered to dominate in producing compositional diversity of igneous rocks, while a more or less inconspicuous part is assigned to assimilation. Positive evidences of differentiation are local and, when attempts are made to explain widespread diversity by this means, many questionable assumptions are required. The writer throws doubt on these assumptions and ascribes a minor part to differentiation. Using thermal evidence for an inductive solution of magmatic problems, he derives the view that most magma is generated by frictional heat during wide and forceful migration and is, therefore, depending on compositional environment, more or less heterogeneous from birth. Without ignoring the local importance of certain processes of differentiation, the view is supported that mass diversity results in the main from heterogeneity of parent magma and not from differentiation in homogeneous magma chambers.

INTRODUCTION

Compositionally different igneous rocks frequently occur in a manner that suggests community of origin, as in the case of a succession of lava flows from a single vent. In each of many groups some degree of serial diversity is observed and is taken to indicate consanguinity or a relationship of the members to a common parent magma which is less heterogeneous than its products and may be nearly homogeneous. Serial diversity seems to imply either the splitting of parent magma into fractions of differing composition or contamination of the magma in varying degree by solution or absorption of material of different composition. These two processes are known to petrologists as "differentiation" and "assimilation," respectively. It is well established that both processes operate to bring about diversity, but direct evidences are in each case decidedly local. When, however, attempts are made to establish which process is the more important in the mass production of diversity, much depends on the choice that is made from remote and often indirect evidences. For instance, if the sum of the evidences were taken as indicating that intrusion is usually passive, differentiation would be favored, while forceful intrusion points rather to assimilation. A so-

lution of the problem of diversification has proved so baffling from a study of effects that inductive methods of arriving at the truth should receive every consideration.

At the present time differentiation is considered to be of great importance by most petrologists—a dominant process by a majority and an almost exclusive process by an important number. Many ways have been suggested by which a homogeneous magma might differentiate to yield compositionally different rocks, but there is little agreement as to the process or processes which are most effective.

Evidences of assimilation are substantial enough locally, but its broad importance is severely questioned by many. Its effectiveness is doubted, however, not because it does not equally well permit an explanation of consanguinity and serial diversity, but on the grounds that there is insufficient heat for important contamination of parent magma. This argument against surplus heat for assimilation is not well founded. It is based on concepts of the generation and intrusion of magma which rest, in turn, on questionable assumptions needed to make differentiation a widely applicable process.

The favored processes of differentiation function as a consequence of slow cooling and crystallization, so that it has been found necessary to assume that accumulations of magma occupy "subcrustal" or "intercrustal" regions and remain in comparative quiet during long intervals. It must be further assumed that magma reservoirs are of enormous thickness and areal extent, when the hypothesis is expanded to explain the great accumulations of granite and related acidic rocks. These great masses are interpreted as being outward expressions of differentiation in homogeneous basaltic magmas which are assumed to rise passively into shallow levels. The writer holds that thermal evidence is opposed to the assumptions on which the differentiation hypothesis in its wider ramifications has been built. He favors the views that magmas are largely generated by frictional heat in widely disposed sheets which migrate through varying compositional environments, and that intrusion is forceful and a cause rather than an effect of deformation. An attempt will be made, therefore, to show that igneous rock diversity is accounted for in the main by heterogeneity of parent magma.

ASSUMPTIONS UNDERLYING CONCEPTS OF DIVERSIFICATION

Serial diversity in a unitary mass of igneous rock is in some cases considered to be more convincingly explained by differentiation than by assimilation. Especially is this true where it seems that diversification followed intrusion, as in certain sills and laccoliths. Here is found the most direct and positive evidence of differentiation from homogeneous magma, and in these cases also the argument against surplus heat for assimilation appears well established. In the more important, because more numerous and larger-scale, associations of separate consanguineous units of igneous rock, or diverse portions of a batholithic unit, there is little or no evidence of a direct or positive nature favorable to an important operation of either process. Here, if initial homogeneity is assumed, all that can be safely predicted is that either differentiation or assimilation, or perhaps a combination of these processes, contributed to diversification before the final emplacement of the respective units or portions. From this stage in the solution of the problem, where much doubt should govern, advocates of differentiation make bold assumptions which seem to permit the working of that process and to minimize the importance of assimilation.

To explain diversification into large masses by differentiation the assumption is usually made that great reservoirs of homogeneous magma persist under passive conditions and so permit the operation of the favored process. According to some authorities[1] evidences require that parent magma splits into compositionally different *liquid* portions before the advent of crystallization. Such a process is not consistent with the known behavior of silicate melts, and there is cause for wonder why liquid differentiation is assumed in many instances when the simpler assumption that the parent magma was never homogeneous might explain effects more readily. If diverse igneous rocks reflect similar diversity in entirely liquid parent magma, it seems likely that the parent was never otherwise than diverse and that a blending process, rather than one of differentiation, contributes to serial diversity.

[1] L. V. Pirsson and A. Knopf, *Rocks and Rock Minerals* (New York: Wiley, 1926), p. 177; W. H. Collins, "Life-History of the Sudbury Nickel Irruptive," *Trans. Royal Soc. Canada*, Vol. XXVIII, Section IV (1934), pp. 123–77.

More commonly appeal is made to a process of differentiation which involves crystallization from a homogeneous parent. This process is more firmly established than that of liquid differentiation, since it is supported by more direct and positive field evidence as well as by experiment, but it faces many difficulties. According to Harker:

> If . . . . we are to apply to the earlier unknown differentiation the same principles which appear to be valid in relation to differentiation in place, it seems necessary to assume that crystallization and re-fusion occur, sometimes repeatedly, in the intercrustal magma-reservoirs.[2]

The differentiation hypothesis encounters, therefore, the most serious objection raised against assimilation, namely, sources of heat for melting. This is typical of the difficulties which beset differentiation when its processes are tested by effects. The uncertainty surrounding the means of diversification justifies the conclusions of Fenner:

> If we regard matters in as unbiased a manner as possible I think we shall have to admit that for most of the differentiated igneous bodies that have been studied there is not yet apparent any complete explanation as to the cause or causes of variation. Gaseous transfer, crystallization differentiation, assimilation of foreign material, and mingling of magmas have apparently each played a prominent part in one or another described instance, but it is impossible to say what is the quantitative importance of any one of them in volcanism as a whole, or whether there may not be still other important processes.[3]

Notwithstanding the many uncertainties surrounding the explanation of diversity, there are signs that entrenched assumptions are dictating views. The custom has grown of referring to diverse members of a consanguineous group as products of differentiation in a chamber of homogeneous magma below, yet in many cases the explanation of diversity taxes alike the ingenuity of the inventor and the credulity of the reader. Processes are overworked, for example, in attempts to explain the many divergent sequences of lava flows. The view that original parent magma approaches homogeneity is perhaps more firmly entrenched than any concerning the manner of diver-

[2] Alfred Harker, *The Natural History of Igneous Rocks* (New York: Macmillan, 1909), p. 311.

[3] C. N. Fenner, "The Katmai Magmatic Province," *Jour. Geol.*, Vol. XXXVI (1926), p. 770.

sification, yet the view is based on assumption rather than on evidence.

Assumptions needed to make differentiation widely applicable have influenced the formation of views on tectonic problems. An intimate connection between deformation and intrusion is apparent on all sides, but the ultimate causes of the association are seldom clear. In sills and laccoliths forceful intrusion is definitely indicated, but whether batholithic intrusion is the cause or effect of mountain folding still challenges discussion. The differentiation hypothesis calls for passive intrusion and, therefore, the view that the rise of the batholithic core of a mountain range is an effect and not a cause of folding. The writer has inductively arrived at the opposing view that deformation is caused by intrusion, which favors the concept of original diversity of magma.

GENERATION OF MAGMA

The ultimate determination of the relative importance of assimilation and differentiation will likely be decided by an inductive solution of the problem concerning the manner of generation and intrusion of magma. With the assumption that the earth solidified from a molten state, the view of Adams[4] that the thick silicate shell crystallized from the interior outward seems reasonable, and the calculation of Jeffreys[5] that the initial thermal gradient has been disturbed to depths of about 700 km. appears to be a fair approximation. The indications are, therefore, that magma formation depends on the generation of radioactive heat. Uniformity of distribution of radioactive elements in the earth's outer shells and a like symmetry in other factors determining thermal conditions would likely lead to the formation of a continuous shell of magma underlying a crust. However, it is well known that the outer shell is very heterogeneous and that isotherms are extremely irregular in outer levels. The writer[6] has shown that small irregularities of distribu-

[4] L. H. Adams, "Temperatures at Moderate Depths within the Earth," *Jour. Wash. Acad. Sci.*, Vol. XIV (1924), pp. 459–72.

[5] H. Jeffreys, *The Earth* (Cambridge: University Press, 1929), p. 154.

[6] J. S. DeLury, "Geologic Deductions from a Thermal Equation," *Jour. Geol.*, Vol. XLIV (1936), pp. 479–95.

tion of radioactive materials will give rise to important differences of thermal history and will likely lead to local generation, forceful and wide migration, and active intrusion of magma.

The differentiation hypothesis, as widely accepted, seems to require the passive rise of homogeneous magma into shallow levels to form enormous, thick, and widely disposed reservoirs. Thermal evidences, however, appear to be opposed to this concept. They suggest rather that magma is generated in widespread sheets in environments which are unstable and favor forceful migration. The same evidences lead to the view that magmas are largely generated by frictional heat from subsidence,[7] the energy for which comes ultimately from original heat sources through the medium of thermal distortion.[8] This concept of the generation and activities of magma favors the view that assimilation is the guiding process of diversification of igneous rocks and that youthful homogeneous magma may become increasingly heterogeneous as the magma expands enormously in bulk before final emplacement.

HOMOGENEITY OR HETEROGENEITY OF PARENT MAGMA

Serial diversity in a rock group suggests relationship to a common parent. There is a tendency, consequently, when community of origin is indicated, to assume a homogeneous parent magma. A view has been held that there might be two or more compositional types of parental magma, the differentiation or blending of which might account for the great variety of compositions of igneous rocks. This view seems to be losing ground in favor of another which holds that all igneous rocks are derivatives of a single compositional type of magma, or as expressed by Daly: "With Bowen, and now Harker, Smyth, and others, we may agree that the only post-Cambrian primary magma has been basic and the author regards it as dominantly basaltic."[9] Besides being unsympathetic to the view that igneous processes were radically different in pre-Cambrian and post-Cam-

[7] DeLury, "Magmas from Subsidence," *Amer. Jour. Sci.*, Vol. XXIII (1932), pp. 357–68.

[8] DeLury, "The Strength of the Earth," *Jour. Geol.*, Vol. XLI (1933), pp. 748–56; "The Magmatic Wedge," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 341–52.

[9] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill, 1933), p. 332.

brian times, the present writer sees no evidence that definitely supports the contention that primary magma has been in later times all basaltic or even dominantly of a single compositional type.

Viewed in a broad way, there appear to be no great differences between pre-Cambrian and post-Cambrian igneous products. The differences commonly cited may be more apparent than real and, therefore, not essential. Igneous processes seem to depend primarily on thermal conditions. A marked change in these processes would spell a marked change in heat sources. The suggested evolution in igneous activity took place at what, according to the best estimates of geologic time, would be the three-quarter mark in that time. In view of the nature of heat sources such a break in the even course of igneous activity is not expected. A radical change would be more comprehendible in early geologic time, but not in the last half during which there is no reason for supposing more than very minor thermal changes.

The concept of the universality of basaltic magma as a source of all igneous rocks seems to have grown with the body of assumptions needed to make differentiation a competent process. It is held, for instance, that the exposed granite batholith is a differentiate of a passively intruded basaltic magma which must have been of great thickness to yield such an enormous acidic fraction. The evidence of the existence of a continuous basaltic shell is useful but offers in itself no basis for this concept. Perhaps the best support comes from the wide distribution in time and space of extensive flows of remarkably uniform basalt. This may aid the concept of homogeneity of parental magma, but there is cause for wonder, with differentiation a dominant process in basaltic reservoirs, why the great extrusions are so uniform in composition from flow to flow. This is essentially the same difficulty facing differentiation as an effective process that is presented by the contrast between volcanic products of deep ocean basins and those of continents. The former typically show few or no acid lavas, while continental volcanoes usually contain such rocks and commonly possess a greater variety. The most obvious interpretation to be drawn from lavas in their world-wide distribution is that they portray in a rough way the degree of heterogeneity in those parts of the earth which were tapped to produce them.

The writer holds that primary magma may at times be nearly homogeneous, but that it is more commonly generated in environments which decree heterogeneity. In his view magma is generated initially by pure melting under a limited area and in a very restricted vertical horizon. This youthful magma probably in most cases approaches homogeneity. Established as a horizontally disposed sheet, the youthful magma is forced to migrate widely, and in its migration more and more magma is generated by frictional heat until the final products of melting form many times the bulk of youthful magma. If generation and migration are throughout in rocks of uniform composition, little diversity is expected in the finally emplaced products. If, on the other hand, there are a wide migration and a generation of magma from diverse rocks, consolidated products will exhibit a similar diversity. There will commonly be a gradual transition in composition from place to place in the sheet of magma before intrusion, while its igneous products as exposed to view may show either serial diversity or abrupt changes of composition.

To illustrate, let it be assumed that a sheet of youthful magma is created in the basaltic shell. It will presumably be nearly homogeneous. If the sheet is forced to migrate only through basaltic materials, the magma will grow without important change of composition. It may even migrate through rocks of different composition without material change, if conditions do not favor the generation of magma at that stage. If however, basaltic magma migrates through granitic rocks with the generation of additional magma all the while, all compositions transitional between basalt and granite may exist in the sheet at any one time. The great heterogeneity of the earth's outer shell suggests manifold possibilities for the production of many kinds of serial diversity of igneous rocks.

CONCLUSIONS

Some of the foremost exponents of the differentiation hypothesis have been exclusive in attitude toward the possibility of other explanations of diversity. Harker, for example, stated:

> That the actual diversity met with among igneous rocks and the varying composition of many single rock-bodies are in the main attributable to processes of differentiation is a thesis which needs no formal discussion. . . . . It is clear

that no process of admixture can afford a substitute for differentiation, or enter into consideration as more than a subsidiary factor. The only practical alternative to magmatic differentiation, as accounting for the observed facts, is the doctrine of countless special creations.[10]

Bowen expressed a similar view:

The concept of differentiation is thus an hypothesis proposed to explain various rock associations. The only rival hypothesis ever proposed was the doctrine of the mixing of two fundamental magmas (basaltic and rhyolitic) but this has been found to fail so completely that the concept of differentiation has come to be regarded as a fact as well established as the observed rock associations themselves. Only the processes which bring about differentiation are ordinarily regarded as of hypothetical character.[11]

The present writer fully admits the evidences that differentiation processes operate locally, and it may be that they are of great importance, but the sweeping conclusions in the foregoing quotations can hardly be justified. Local diversity of igneous rock seems to be well explained in some instances by differentiation, but mass diversity constitutes a different problem. It is not impossible, of course, that some of the processes of differentiation may operate during the migration and generation of magma in conjunction with assimilation and thereby contribute in producing diversity.

The question of homogeneity or heterogeneity of parent magma gives rise to others still more fundamental. The origin of sial and, therefore, of continents is involved. Was sial inherited from the geologic birth of the earth or has it been slowly differentiated from basaltic magma? Does the sum of the activities of all geologic agents spell a greater "mixing" or "unmixing" of earth materials?

It is well known that the continents are built in the main of batholithic sial. Unless pre-Cambrian igneous processes are marked off as being different, the differentiation hypothesis implies more or less that the early geologic outer shell of the earth has been destroyed bit by bit by the outward invasion of successive passively rising basaltic magmas. This further implies a mixing of earth materials and the destruction of any sial that might have been inherited from geologic birth, also the building of continental masses during the

[10] *Op. cit.*, p. 310.

[11] N. L. Bowen, *The Evolution of the Igneous Rocks* (Princeton: University Press, 1928), pp. 3–4.

geologic record by sial slowly created from the differentiation of basaltic magma. According to this hypothesis, then, batholithic processes are both destructive and constructive, but with a net result favoring an increase of sial. It is known, moreover, that there were segregations of sial and that continental masses existed at the beginnings of the geologic record. But geologic time might be far longer than the record. If sial was largely inherited, a mixing of earth materials would tend to decrease its total mass. On the other hand, if it has been differentiated during geologic time, its mass may be steadily increasing. Because he accepts the view that mixing dominates over unmixing in igneous processes, the writer favors the concept of an inherited shell of sial. This would imply original differentiation of the earth as a whole, which seems highly credible from the evidences of compositional zoning and the uniformity of composition of plateau basalt.

It is known that borderlands disappear at times when granite masses are being lodged in the mountain cores of mobile belts. Moreover, continents appear to have been built largely by granitic rocks formed in the activities of successive and migrating mobile belts. Is it not credible, in view of these evidences, that continents represent the skimmings of a shell of sial which originally might have been more evenly distributed over the earth's face?

MESOZOIC GEOLOGY OF THE RITTER REGION SIERRA NEVADA, CALIFORNIA

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ABSTRACT

The Ritter region lies near the crest of the Sierra Nevada, southeast of Yosemite National Park, California. It is composed of an "attached roof remnant" which consists largely of metamorphosed pyroclastic rocks that have been invaded by small forerunners of the Sierra Nevada pluton.

The composition and structural relations of the various rock masses are discussed. It is concluded that space for the intrusions was created largely by forceful displacement of the meta-volcanics.

Two directions of regional discordance are noted, and their possible importance to the problem of intrusion is suggested.

INTRODUCTION

In a previous report, published by the California State Division of Mines,[1] the writer discussed the general and economic geology of the Ritter region—a rugged mountainous area, situated near the crest of the Sierra Nevada, and adjoining the Yosemite National Park on the southeast. The Ritter region fills a re-entrant between the area investigated structurally by Ernst Cloos[2] to the north and that investigated by E. B. Mayo[3] to the east and southeast. The geologic interest of this area in relation to adjoining, recently studied regions makes it worth while to publish, in more accessible form, the Mesozoic geology of the Ritter country. In the following discussion interest is directed chiefly to a consideration of the pre-Cretaceous crystalline rocks. Younger features will not be considered.

REGIONAL SETTING

The topographic climax of this region is the imposing, northwest-trending Ritter Range, of which Mount Ritter (13,156 ft.) is the

[1] H. D. Erwin, "The Geology and Mineral Resources of Northeastern Madera County, California," *Calif. Jour. Mines and Geol.*, Vol. XXX (1934), pp. 7–78.

[2] "Der Sierra Nevada Pluton," *Geol. Rundschau*, Vol. XXII, Heft 6 (1931), pp. 372–84.

[3] "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *Jour. Geol.*, Vol. XLIII (1935), pp. 673–89.

culminating peak and the picturesque Minarets the southern continuation (Fig. 1). The Ritter Range, although situated some 12 or 14 miles west of the Sierra Nevada crest, dominates the region; the dark crags of Mount Ritter and the Minarets look over the Sierra crest to the Great Basin beyond. The western slope of the range is drained by the north fork of the San Joaquin River; the middle fork flows southward between the Ritter Range and the Sierra crest.

FIG. 1.—Ritter Range from the east. Photo by Erwin E. Richter

The crystalline rocks of the region are divisible into two major groups: (1) pre-intrusive formations—a series of intensely folded, steeply dipping meta-volcanics, with minor intercalations of meta-sediments—and (2) vast granitoid intrusions, belonging to the Sierra Nevada pluton. The metamorphics are thought to be mostly of Triassic age because identical rocks occupy the same relative position in the Sierra Nevada to the south and have been assigned to the Triassic by A. Knopf.[4] They rest like a huge, ragged shield on the eastern border of the pluton. The shield has been penetrated by

[4] "A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Sierra Nevada, California," *U.S. Geol. Surv. Prof. Paper 110* (1918), p. 48.

a number of basic forerunners and by minor intrusions of micropegmatitic granite. At one place the intrusions have split the shield almost in two (Fig. 2).

METAMORPHIC ROCKS

Nature and origin.—The metamorphic rocks are an assemblage of steeply dipping gray strata or interlocking lenses that trend about N. 40° W. The component strata vary markedly in lithology and in color; some members are almost white, while others are very dark, somber gray.

There is abundant evidence to show that most of the metamorphic rocks are of volcanic origin. Under the microscope partially resorbed but unbroken quartz phenocrysts—paramorphs after β quartz—have been found in some of the less-sheared acid members. In darker members deformed gas cavities, filled with epidote and chlorite and strongly pressed fragments of basaltic lapilli, now outlined by swarms of minute magnetite crystals, tell of basic lavas that have undergone metamorphism. The original fluidal structures of the lavas are locally preserved; but, as fragmental types predominate, an original pyroclastic structure, more or less modified by subsequent shearing, is much more common (Fig. 3).

The heterogeneous assemblage, in which meta-tuffs predominate, indicates a mixed volcanism, characterized by much explosive activity. Fortunately, there is local evidence which permits further deductions as to the conditions under which these rocks were formed. At two localities sheared rhyolites occur which carry swarms of ellipsoids or nodules (Fig. 4). The significance of such structures has not been established with certainty, but all the occurrences that have come to the writer's attention are interbedded with a regular marine sequence.[5] Layers of well-sorted and rounded volcanic sandstones and conglomerates that have survived the metamorphism are

[5] T. G. Bonney, "On Some Nodular Felsites in the Bala Group of North Wales," *Quar. Jour. Geol. Soc. of London*, Vol. XXXVIII (1882), pp. 289–97; A. K. Wells, "The Geology of the Rhobell Fawr District" (Merioneth), *Quart. Jour. Geol. Soc. of London*, Vol. LXXXIII (1925), p. 517; Howell Williams, "The Geology of Snowdon" (North Wales), *Quart. Jour. Geol. Soc. of London*, Vol. LXXXIII (1927), p. 364; Howell Williams and O. M. B. Bulman, "The Geology of the Dolwyddelgh Syncline" (North Wales), *Quart. Jour. Geol. Soc. of London*, Vol. LXXXVII (1931), p. 432.

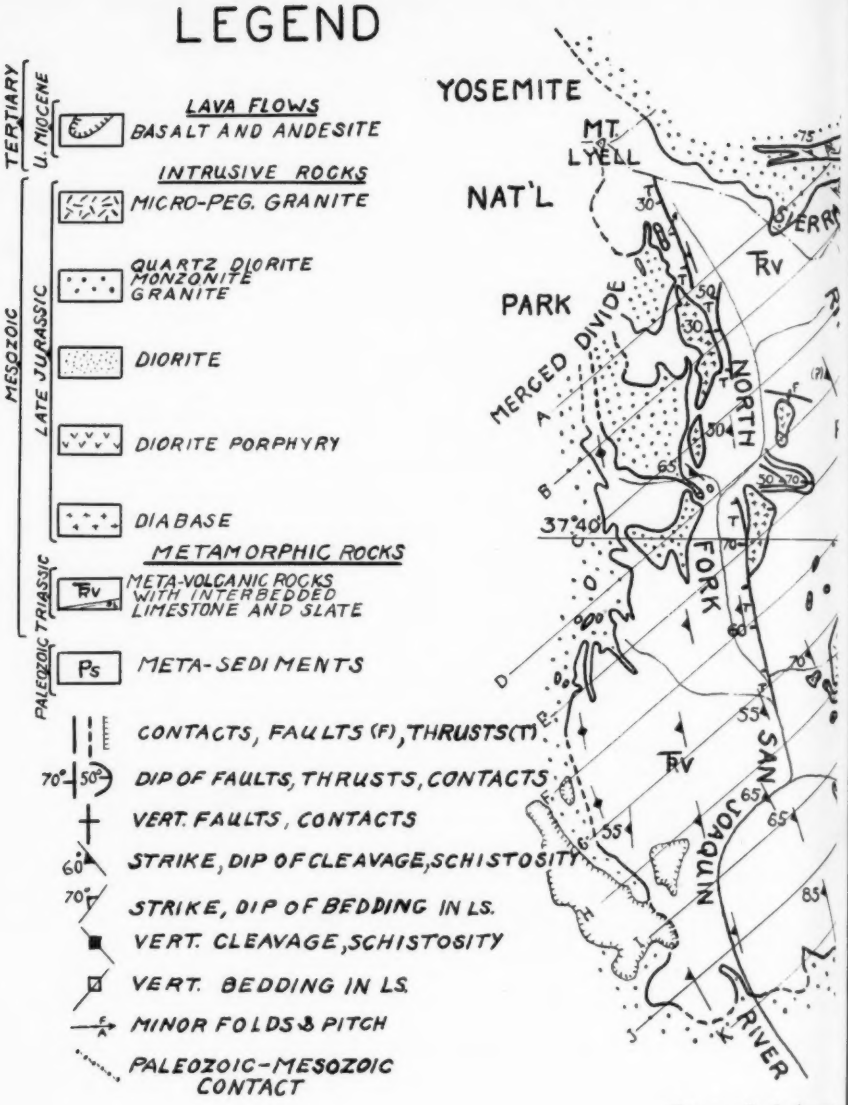
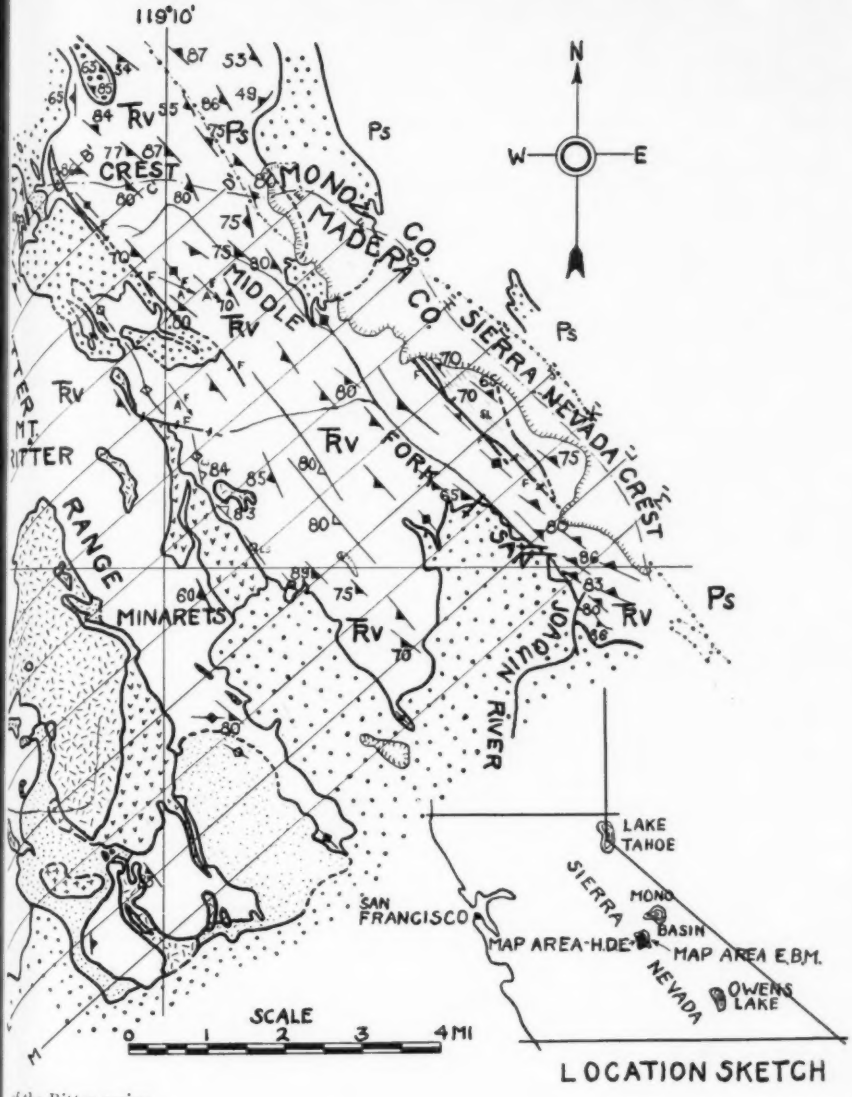


FIG. 2.—Geologic map



of the Ritter region

locally present. The constituent, well-sorted and rounded grains and pebbles are mainly fragments of basic lavas. In some cases these rocks retain a reddish-brown color caused by oxidation before

FIG. 3.—Meta-volcanic breccia, west side of Ritter Range

FIG. 4.—Metamorphosed nodular rhyolite

lithification. Most conclusive are minor intercalations of normal marine sediments. These now occur as slate and crystalline limestone or marble.

Metamorphism.—Cataclasis was the dominant feature of the metamorphism. Most of the rocks have been crushed—some of them intensely—and commonly the crushed materials have been strongly milled. In consequence of the shear that they have undergone, the rocks have assumed a cleavage. Ordinarily, this cleavage is best

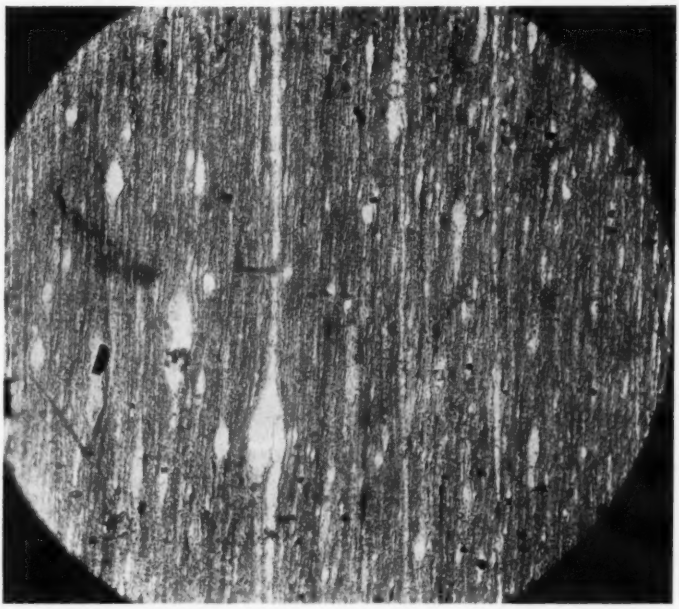


FIG. 5.—Photomicrograph of slate showing rolled fragments of quartz in a dark graphitic matrix. Cleavage follows the shear direction. 60 diam. ordinary light.

developed in zones which have been occupied by relatively non-resistant tuffs and ashes or argillaceous sediments (Fig. 5). It may be totally lacking in some of the more resistant types, as for instance in the rocks which compose the Ritter Range, whereas the rocks in broad areas flanking the range exhibit good cleavage. There are three possible explanations for the massive character of the rocks of the Ritter Range. (1) The rocks on either side of the range, nearest the major intrusions, may have taken up most of the adjustment owing to igneous emplacement and left a central core relatively

unaffected. (2) It is also possible that the rocks of the Ritter Range were so indurated by emanations from early basic intrusions that cleavage was not produced by compressive stresses. (3) Effects produced by emanations may have erased an earlier cleavage. The last of these possibilities is the favored one.

Associated with granulation and shear there has been some recrystallization and formation of new compounds. In the more acid members, sericite, actinolite, small amounts of epidote, and rarely piedmontite have been produced locally along zones of especially intense movement. The dark, basic members and the limestones were more susceptible, but the thermal effects of metamorphism were comparatively slight, although the dynamic effects were very intense.

As the cleavage is locally abruptly transsected by granitic intrusions, most of it was formed before emplacement of the pluton. Crushing and mylonitization were the results of intense folding which produced the very steep dips characteristic of the area. The metamorphic rocks preserve a record of a period of explosive vulcanism, associated with a marine environment, and followed by a period of intense folding. The next episode in the pre-Cretaceous history involves the igneous invasion.

IGNEOUS ROCKS

Toward the close of the period of folding, the region was invaded by enormous volumes of magma. The pluton resulting from this invasion was not emplaced all at one time as a single, regional unit but was gradually built up in successive increments, generally emplaced in order of increasing silicity. Wherever the time interval between successive intrusions was great enough, sharp, definite contacts now separate the resulting plutonic types; but gradational contacts are not uncommon.

The age of this plutonic complex cannot be determined directly in this area. The intrusions invade, and are therefore plainly younger than, the supposed Triassic rocks. The pluton has long been regarded as of Upper Jurassic or Lower Cretaceous age, and recent evidence[6] favors the former.

[6] N. E. A. Hinds, "The Jurassic Age of the Last Granitoid Intrusions in the Klamath Mountains and Sierra Nevada, California," *Amer. Jour. Sci.*, Vol. XXVII (1934), pp. 182–92.

The early stages of magma emplacement are exceptionally well recorded in the Ritter region. So far as known, the forerunners of the invasion are displayed to better advantage here than in any neighboring region—a condition which makes this an area of particular interest from the standpoint of the intrusion history.

FORERUNNERS

The forerunners now appear as dark intrusive bodies, relatively small, or moderate, in size. As shown on the map (Fig. 2), their distribution in and near the roof pendant seems to be controlled largely by structural trends in the meta-volcanics. The largest forerunners (together with the largest body of micro-pegmatitic granite, to be discussed later) occur in the Ritter Range. There may be some relation between the location of these intrusions and the commanding height of the present mountains.

The earliest magmas are more basic than the larger bodies which followed but show marked affinities with the main body of the pluton. The earliest intrusions are dominantly calc-alkaline, low in quartz, and high in femic minerals. The prevailing feldspar is andesine or oligoclase. Hornblende and biotite are the dominant femic constituents; the virtual absence of any pyroxene is a feature common to all intrusive rocks of the region, and it may signify a "wet" magma province in the sense of Buddington.[7] Volatile constituents, escaping from the cooling masses, have left their record in the saussuritization of the feldspars and in the development of abundant epidote and chlorite. The accessory minerals are those common to the granitic rocks of the Sierra: magnetite (or titanomagnetite), apatite, sphene, and zircon. Their distribution in the various types of forerunners will be considered below.

The forerunners are divisible into three lithologic types: (1) andesine-diabase, (2) diorite-porphyry, and (3) diorite.

1. In the diabase the predominant mineral is andesine, which occurs as subhedral to euhedral crystals 2–5 mm. long. These are in a rather sparse matrix, essentially of biotite and hornblende. The resulting texture is plainly ophitic. Only magnetite and apatite are represented among the accessories.

[7] A. F. Buddington, "The Adirondack Magmatic Stem," *Jour. Geol.*, Vol. XXXIX (1931), pp. 240–63.

This rock is almost entirely restricted to the western border of the metamorphic area. One mass, located near the southern margin, is surrounded and intruded by diorite.

2. In the diorite porphyry the andesine (less abundant than in type 1) and oligoclase occur as euhedral phenocrysts in a fine-grained to dense dark-green matrix. Sphene joins magnetite and apatite as an accessory.

It is not known whether diorite-porphyry or andesine-diabase is the earlier intrusive rock because the two types were never seen in contact, but both were invaded by type 3.

3. Medium-grained, nonporphyritic diorite penetrates the southern margin of the roof pendant, having come in shortly before the emplacement of the later main granitoid intrusions. In this diorite, oligoclase accompanied by minor amount of orthoclase takes the place of the andesine that occurs in the earlier forerunners. A little quartz and zircon are also present.

THE PLUTON

Wherever a part of the main plutonic mass was seen in contact with diorite, the diorite was the invaded rock (Fig. 6). As stated before, the regional invasion occurred in increments and not all at once. The pluton is therefore composite, but in this paper it has to be treated as a unit because the contacts between individual batholithic intrusions were not mapped.

The rocks vary in composition from granodiorite to aplitic granite. The latter occurs sparingly as small bodies that traverse all other intrusions. Most of the rocks are even-grained, but the youngest of the larger masses (which occurs in the southeastern corner of the area) is a porphyritic quartz-monzonite, with huge phenocrysts of potash feldspar. This is thought to be the equivalent of the Cathedral Peak granite. Likewise, the larger mass of nonporphyritic granitic rock south, southwest, and west of the roof pendant may be equivalent to the Half Dome quartz-monzonite. Both of these types have been recently described by F. C. Calkins.[8]

The mineralogical variations from the latest of the forerunners (diorite) through the intrusive sequence in the pluton are relatively simple. The oligoclase, characteristic of the diorite, persists with

[8] *U.S. Geol. Survey Prof. Paper 160* (1930), pp. 120–26.

relatively slight increase in the albite molecule. Only in a few of the aplites is the mineral albite present. Plagioclase decreases in amount as the intrusions become more silicic and a potash feldspar becomes more abundant. Quartz also increases, while the mafites decrease. Hornblende gives way almost completely to biotite in the youngest, most silicic intrusions. The total amount of accessory minerals decreases somewhat, but none of the four, mentioned above, entirely disappears. Alteration products, abundant in the more basic fore-

FIG. 6.—Quartz monzonite (light) intruding diorite (dark), near southern border of the roof remnant.

runners, are less important in the later rocks but seem always present. A slight development of sericite in the feldspars is not unusual. Epidote, though far from abundant, is never absent, while the biotite is always slightly altered to chlorite.

Small, dark inclusions are very abundant in the even-grained intrusions. They are rare in the younger porphyritic quartz-monzonite, except in the immediate vicinity of the eastern wall, where this intrusion comes in contact with meta-volcanics. Pabst[9] states that such enclosures never show gradations toward any of the exposed wall rocks. He terms the inclusions "autoliths," thereby implying that they are segregations from the magma. The lack of gradation into inclusions which resemble near-by wall rocks is

[9] A. Pabst, "Observations on Inclusions in the Granitic Rocks of the Sierra Nevada," *Univ. Calif. Dept. Geol. Bull.* 17 (1926), p. 358.

explained if the inclusions are fragments that have reacted considerably with the magma and have been carried upward. Gradations may have been destroyed by translation of the fragments along the wall. So far as the writer is aware, no real proof has been offered that these inclusions are cognate. They may be xenoliths. This question is of vital importance; its proper solution would greatly aid the understanding of intrusive processes.

MICRO-PEGMATITIC GRANITE

As shown on the map, a large stock and several outliers of micro-pegmatitic granite have invaded both the metamorphics and the basic forerunners. This rock is a pale-pink to flesh-colored granite with quartz and orthoclase the most apparent minerals. A finely crystalline border phase is common, while a porphyritic texture is apparent within the intrusion.

The presence of a chilled border indicates that the micro-pegmatitic granite forms a normal intrusion and is not the result of replacement. A replacement origin has been suggested for granites with texture similar to this one.[10]

Under the microscope a spectacular graphic intergrowth of quartz and orthoclase appears (Fig. 7). A small amount of oligoclase and microcline is also present. The plagioclase occasionally occurs as perthitic intergrowths in orthoclase. Quartz occurs in myrmekitic structures at the contacts of orthoclase and plagioclase. The striking mineral intergrowths are probably the result of deuteric reactions.

Bright-green hornblende and biotite are sparingly present. The former is perhaps the more common. Titaniferous magnetite, sphene, and zircon complete the list of accessory minerals.

On the basis of mineralogical composition, this granite is thought to be younger than the main pluton, although the contacts which would furnish conclusive evidence have not been observed.

STRUCTURES

The structural features (Fig. 8) of the area will be considered as nearly as possible in the order of their formation because this should bring out most plainly the changes imposed by successive events.

[10] James Gilluly, "Replacement Origin of the Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Paper 175c* (1933). Pp. 16.

The earliest structures of which there is any record have been mentioned in the discussion of the metamorphic rocks. They include primary flow banding of the lava members, the crude bedding caused by alternation of original tuffs and flows by intercalations of normal marine sediments, and the finer bedding due to the sorting effect of currents on the finer clastic materials.

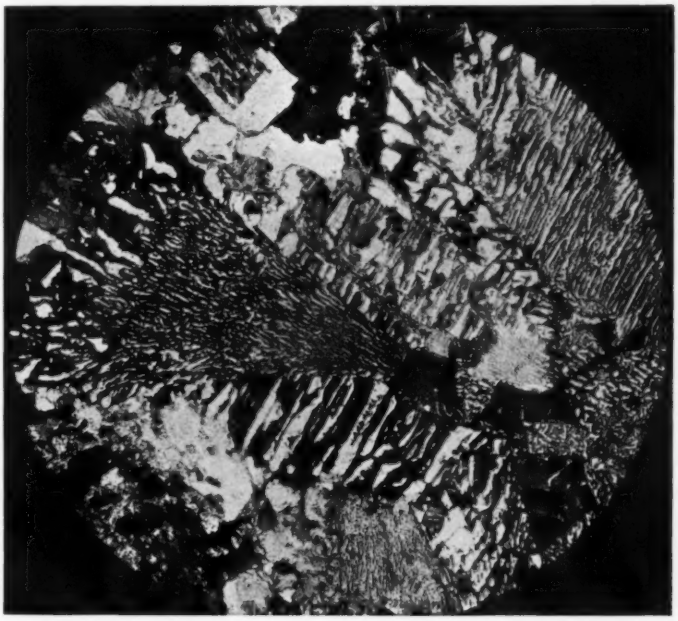


FIG. 7.—Photomicrograph of micro-pegmatitic granite showing pronounced graphic intergrowth of quartz and orthoclase feldspar. 50 diam. crossed nicols.

In the late Jurassic these oldest structures were folded previous to the igneous invasion, and cleavage was developed as a regional feature.

FOLDING

Nature of folding.—Two facts concerning the metamorphic rocks are evident in the field: (1) Where cleavage and bedding occur together, they are nearly always parallel in strike and dip; and (2) no

major folds are apparent, and only locally can the axes of minor folds be found.

The first observation suggests isoclinal folding; and the second probably follows as a natural corollary; since, whenever folding has

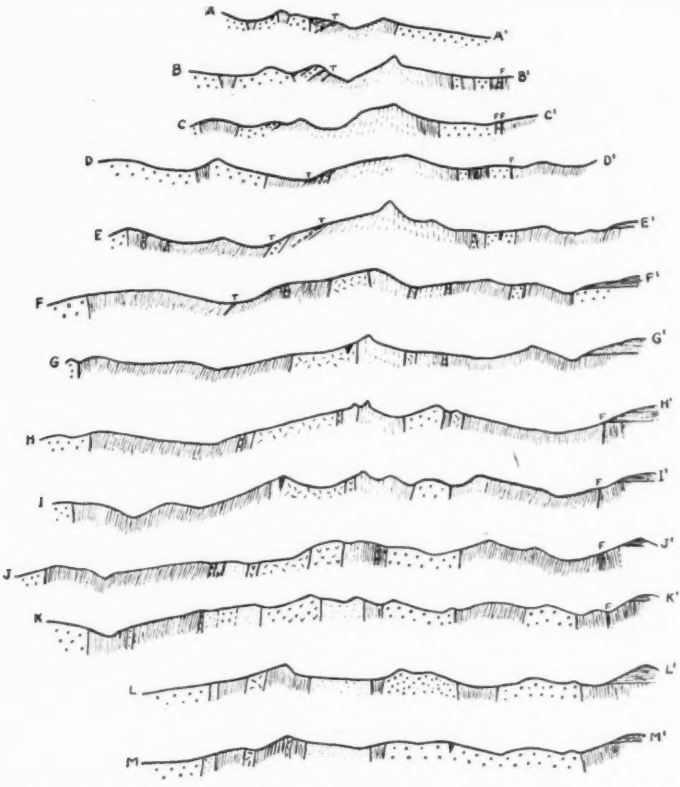


FIG. 8.—Geologic cross-sections of the Ritter region. Igneous rocks represented by the same symbols as on the geologic map of the region (Fig. 2). The metamorphics shown by dashed and broken lines.

been intense, there is a tendency for crests and troughs to be erased through reorientation of minerals parallel to the cleavage.[11] It is

[11] Robert Balk, "Inclusions and Foliation of the Harney Peak Granite, Black Hills, South Dakota," *Jour. Geol.*, Vol. XXXIX (1931), pp. 739–40.

possible, also, that some of the difficulty in locating the axes of major folds lies in the character of the original deposits. These may have included, besides extensive layers of ash or flows of fluent lava, many thick, local lenses of clastic materials, stubby flows of viscous lava, and possibly massive protrusions. It is doubtful if any regular system of major folds could develop in such a section.

Over the entire area of cleaved metamorphic rocks, strike faults furnish abundant evidence of adjustment between the dissimilar rock members. These structures commonly form a break in slope along the transverse ridge summits.

Regional attitude of folding.—As shown on the map, there is considerable variation in the strikes of the metamorphic rocks; however, the prevailing direction is about N. 30°–40° W., parallel to the trend of the Sierra Nevada. It cannot be assumed that the original strike of folding held strictly to this direction because there must have been local variations. It is thought, however, that the initial changes of trend were of minor importance and that certain striking variations found today require a special explanation.

Bedding and cleavage dip steeply (60°–90°) and mostly toward the southwest. This system of isoclinal northwest-trending folds formed the structure encountered by the plutonic mass. It remains to be seen to what extent the folded rocks of the area have guided intrusions.

STRUCTURAL RELATIONS OF THE INTRUSIONS

When the writer did the field work, he was unfamiliar with the Cloos methods, and for this reason few data were secured concerning structures within the intrusions. The behavior of the magma has to be inferred from relations of intrusive form to wall-rock structures. The effects of forceful emplacement were not fully realized when the field work was done. In a way, this was an advantage, since the concept of forceful emplacement could have no influence on the selection of data.

Before emplacement of the major plutonic mass, the metamorphic rocks were pierced by many small stocks, dikes, and irregular bodies of basic magma. The largest intrusive center seems to have been south of Mount Ritter, in the area now occupied mainly by a large mass of micro-pegmatitic granite.

BASIC FORERUNNERS

As shown on the map (Fig. 2), all but one of the andesine-diabase intrusions occur in a zone of thrusts and relatively gentle dips (60°–30°) near the western margin of the roof pendant. Here the diabase forms tabular masses, conformable with the enclosing rocks. Apparently, the magma has utilized such planes of weakness as cleavage or possibly thrusts. If the latter formed the control, then thrusting from the west may have commenced long before the larger granitic bodies appeared in this area. The thrusts shown on the map, however, are plainly later than the basic intrusions.

It is possible that the diabase, which is composed essentially of plagioclase crystals, was formed by filter-pressing of partially crystallized magma along the earliest thrust planes. A similar process, operating on a regional scale, is thought to have produced the anorthosite and related rocks in the Adirondack Mountains of New York.[12] It is not known whether the single diabase body near the southern margin of the area will conform to this interpretation, since it is completely surrounded by diorite, with loss of its original structural relations.

Four features of the diorite porphyry are worthy of mention.

1. In the small area of nearly east-west trends, east of the main area of micro-pegmatitic granite, the rocks form an igneous-metamorphic complex in which myriads of dikes of diorite-porphyry and diorite have followed the cleavage planes of the metamorphics (Fig. 9). This intimate invasion of wall-rock structures must represent an early stage of the intrusive process.

2. Near the center of the rock pendant, elongated intrusions, which nearly split the pendant in two, indicate a zone of weakness. The shape of the diorite porphyry in this zone supports the evidence presented under (1) and plainly indicates control by the wall-rock trends.

3. At an early stage in its history, the intrusive center south of Mount Ritter may have consisted entirely of diorite-porphyry. In view of the observations presented under (1) and (2), it is probable that this rather large body at first inserted itself as a thin tabular

[12] Robert Balk, "Structural Geology of the Adirondack Anorthosite," *Min. u. Petrog. Mittheilungen*, Vol. XLI (1931), pp. 308–434 (esp. pp. 404–11).

mass parallel to the cleavage of its wall rocks. The mass (together with later micro-pegmatitic granite) still conforms generally to wall-rock trends, but the outlines of the body no longer follow the older structures in detail. Moreover, the width of the mass now exceeds a mile. How was the magma chamber so widened?

There has been considerable shattering of the invaded rocks with production of cross-cutting contacts. Such conditions would doubtless favor overhead stoping; but, if this has been the chief mode of emplacement, the rareness of wall-rock fragments in the porphyry is

FIG. 9.—Igneous-metamorphic complex at the southern border of the main intrusive rocks.

certainly surprising. Nor is any important amount of assimilation indicated along the sharp igneous contacts. The key to the problem seems to be furnished by the trends of minor intrusions beyond the periphery of the main diorite-porphyry mass.

4. Small masses of diorite-porphyry, and even micro-pegmatitic granite, are disposed in arcuate groups around the larger intrusive center. These small bodies, like the other basic intrusions, have been guided by the wall-rock trends; and these trends obviously represent a modification of the regional one. There are two possible ways in which such structural trends may be caused to swing around an igneous body: external forces may mold the wall rocks to the form

of the solid intrusions or the magma may forcefully thrust aside its walls.

As will be noted later, there has been considerable motion in the wall rocks since the emplacement of the forerunners, but such motion was fairly local and does not seem to have affected this igneous center. There is no general secondary granulation of the intrusive rocks along their borders, and such effects should be found if the trends have been molded to the form of a solid body. Accordingly, it is thought that the invading magma has forcefully thrust aside its walls and that the curving trends so produced have guided the smaller bodies.

It seems, then, that the diorite-porphyry has furnished excellent evidence concerning the initial stage of intrusion and has also indicated how the zones of weakness have been widened. Since the lobate bodies of even-grained diorite show about the same structural features as the later granitoid intrusions, they will not be discussed separately.

THE MAIN GRANITIC MASS

Under this heading is included the intrusive complex, which forms the bulk of the pluton, and which was emplaced after the diorite. The mode of emplacement can be inferred with considerable confidence from the data at hand. They indicate how the magma first moved in the available directions of weakness, then widened these channels of advance, partly by shattering and assimilation, but mostly by forceful displacement of the invaded rocks.

Initial mode of advance.—Above a rising intrusion, evidence of the first stages of injection is progressively destroyed as the magma advances; yet, after an intrusion finally consolidates, some evidence of its advance should still be preserved in the roof and upper portions of the walls. The roof remnant, herein considered, is no exception. Since most of its rocks are cleaved, cleavage or bedding planes are the structures that usually facilitated injection. Uncleaved basic forerunners reacted differently; they shattered irregularly (Fig. 6).

The irregular granitic body projecting into the metamorphics from the north seems to show particularly well the nature of the early stages of emplacement. Detailed study along the contacts has shown that the magma invaded the wall rocks along bedding planes

(Fig. 10). Along the western and northwestern margin of the roof pendant, injection gneisses indicate the same process. Wherever this intimate type of injection prevails, there is usually local evidence of assimilation, particularly where crystalline limestone forms the wall rock.

The first act of the granitoid magma was to penetrate the older formations along all planes of weakness and to assimilate some of those rocks with which it could most readily react. A study of the

FIG. 10.—Granitic rock injected along bedding planes in limestone

outlines of the irregular intrusion, referred to above, shows that the initial processes were eventually supplanted by another. The jagged, cross-cutting contacts clearly suggest that the magma chamber was widened by shattering.

If the blocks produced by shattering were free to sink in the magma, it would be reasonable to assume that the chambers were widened to their final extent by stoping. Few recognizable wall-rock inclusions are to be found in the batholithic rocks. If the large blocks are disintegrated and the resulting fragments digested to form the so-called "autoliths" (dark clots in countless thousands throughout some of the intrusions), it may be that the lack of recognizable xenoliths is not a good criterion. These clots are most abundant in the quartz-monzonite and lacking or rare in the Cathedral Peak

granite. It seems better to consider the final stages of intrusion in order to see if the stoping hypothesis is necessary.

Broadening of the magma chamber.—If the same irregular intrusion, mentioned above, is followed northward, it suddenly broadens into a huge lobate mass. What has become of the rocks which formed the walls for the narrower portions?

Dip and strike readings show that the regional trends have turned. Wall-rock structures swing around the broad lobe. There is some cross-cutting, and some material is unaccounted for (stoped, forced upward, assimilated?), but most of it has plainly been forced aside. The same condition holds true in the case of the other intrusive lobes shown on the map. Thus, the main mass, by confirming the evidence of the forerunners, indicates forceful emplacement. It seems that this conclusion may even apply to the masses of micro-pegmatitic granite. Intrusions of diorite are locally sheared along their contacts with this later, acidic rock.

With the principle of forcible emplacement in mind, some important structure features of the roof pendant can be discussed, as they seem to be modifications caused by intrusion.

FAULTS POSSIBLY RELATED TO INTRUSION

Thrusts.—The andesine-diabase may have advanced along thrust planes; and, therefore, thrusting from the west may have started before intrusion of the basic rocks. The thrusts actually seen and mapped, however, are plainly later then the forerunners. This is especially evident at one locality where thrust sheets, dipping 50°–70° westward, are piled between two forerunners, as ice cakes are carried between the pilings of a bridge.

The relation of these thrusts along the western border of the roof remnant to the huge granitic intrusions immediately westward is noteworthy. The thrusts are parallel to the general trend of the granite contact, and they dip toward the intrusions. Hanging walls have, in every case, moved away from the intrusions, and nowhere does the granite traverse a thrust.

Along the eastern margin of the metamorphics, Mayo[13] found

[13] Personal communication.

many small thrusts that dip eastward, toward an intrusive complex lying beyond the Sierra front. The metamorphics have been compressed from both sides, and it is thought that this fact is responsible for the reversal of dip in the canyon of Middle Fork (see cross sections). The invaded rocks, encroached upon from both east and west, have assumed a roughly anticlinal structure. The axis of this structure is near the eastern edge of the area, probably because thrusting from the west was more vigorous than from the east.

The positions of these marginal thrusts relative to the bordering massifs indicate that the thrusts were developed and utilized in providing space for the aggressive magmas.

Vertical oblique faults.—Vertical faults which obliquely traverse the regional trends are locally developed. One of them occurs north of the pile of thrust slices, referred to above. Another traverses and displaces the long, basic forerunner near the center of the area. Several more occur along the eastern margin of the intrusive lobe in the southern part of the area.

Since some of these faults are nearly at right angles to the structural trends in the area, they may be tear faults. It is thought, however, that they correspond to the oblique shears (striking at 45° to direction of compression) developed experimentally by Mead.[14] In this case, whereas the thrusts on both eastern and western margins of the area indicate outward upward movement, the oblique faults express some additional horizontal shifting.

EAST-NORTHEAST AND NORTH-SOUTH TRENDS

East-northeast direction.—One of the most striking features of this area, in which regional trends were molded to intrusive forms by forceful emplacement of the magma, are the abrupt southern termini of the metamorphics. These termini are not the sharp, appressed forms described by Mayo from a more southernly area. With two exceptions, they are broad, lobate endings that indicate a large-scale discordance of igneous contacts and regional trends.

[14] W. J. Mead, "Notes on the Mechanics of Geologic Structures," *Jour. Geol.*, Vol. XXVIII (1930), pp. 505–23, esp. p. 509.

Mayo has ascribed certain discordances to the structural control of a local shear zone,[15] and it may be that a great zone of shear, trending E.-NE., has occasioned the abrupt southern terminations of the roof pendant. Whatever the cause, the general direction followed by this discordance may be termed the E.-NE. direction.

North-south direction.—All the southern intrusive lobes, except one, trend northwest. The one exception—the easternmost of these lobes—is elongated nearly north-south, and, oddly enough, this direction is also followed by the most prominent Pleistocene and Recent volcanoes of the region.[16]

The writer has no evidence on which to build an explanation of these two discordant regional directions, so further discussion of them is beyond the scope of this paper. It is suggested, however, that a proper understanding of the regional problems of magma emplacement may depend upon a correct interpretation of these directions. They may be as important as the regional trends, discussed under folding. They may hold the answer to the fundamental question as to whether the intrusions, where forceful emplacement is locally so well demonstrated, have accomplished the invasion under their own power, or whether they have been driven into place chiefly by regional tectonic forces.

CONCLUSIONS

In the Ritter Range region the oldest rocks are dominantly of pyroclastic origin and were formed in association with a marine environment. Subsequent to their accumulation, they were tightly folded and subjected to cataclastic metamorphism.

Later, the folded rocks were invaded by a sequence of igneous intrusions. The earliest invaders were basic forerunners; they were followed by the main body of more acidic rocks.

The control of intrusion by wall-rock structures is shown best by the earlier, small masses; the larger intrusions were accompanied by considerable shattering and cross-cutting. A study of faults, thrusts,

[15] *Op. cit.*, p. 681.

[16] E. B. Mayo, L. C. Conant, and J. R. Chelikowsky, "Southern Extension of the Mono Craters, California," *Amer. Jour. Sci.*, Vol. XXXII (1936), pp. 81–97.

and deflections of older structures within the roof remnant shows that the larger masses have forced their walls aside.

It is possible that a key to the relation of igneous intrusion to mountain-folding may be found by a careful study of the east-northeast and north-south regional discordances.

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THE PRICE FORMATION IN THE DRAPER MOUNTAIN AREA, VIRGINIA[1]

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ABSTRACT

The Price formation, the oldest Mississippian formation in the Draper Mountain area, is approximately 1,250 feet thick and consists of sandstone, shale, and conglomerate. Three distinct beds of semi-anthracite coal occur about the middle of the formation. In this general region the Price has been considered by most geologists as continental, but new evidence suggests that in the Draper Mountain area, at least, all except the coal-bearing portion is marine. Fossils indicate that most, if not all, of the Price is of New Providence (Osage) age. The possible Kinderhook age of the lower part of the Price is discussed.

INTRODUCTION

As shown in Figure 1, the Draper Mountain area is in the southeastern part of the Appalachian Valley and Ridge province in southwestern Virginia. It lies to the north, west, and south of Pulaski, the county seat of Pulaski County. The rocks of this area, which range from Lower Cambrian to Mississippian, inclusive, are severely folded and faulted. The Price crops out in a broad belt west of Pulaski between Draper and Brushy mountains.

The writer, while studying the area in co-operation with the Virginia Geological Survey, examined the Price formation in detail. He is also indebted to Dr. Charles Butts, of the Virginia Geological Survey, and to Professor A. K. Miller, of the State University of Iowa, for aid in identifying fossils.

NAME

In 1836 H. D. Rogers, working in Pennsylvania, and W. B. Rogers, working in Virginia, recorded the first systematic study of this formation. They designated by number the various rock units which they were able to recognize and called the formation, now known as the "Price," "No. X." Some twenty years later this numerical method of classification was discarded, and the equivalent formation in Pennsylvania (now known as the "Pocono") came to

[1] Published with the permission of the state geologist of Virginia.

be known in subsequent papers of the Rogers brothers as the "Vespertine." This term was used also in Virginia. In a reprint of the reports of W. B. Rogers on the geology of Virginia, published in 1884, the editor, Major Jed Hotchkiss, substituted in an appended table of formations the name "Montgomery grits" for "No. X" and "Vespertine." The new term was not accepted by Stevenson,[2] who continued to use "Vespertine." Hotchkiss failed to define his new term and to relate it to the two equivalents used by Rogers, but he

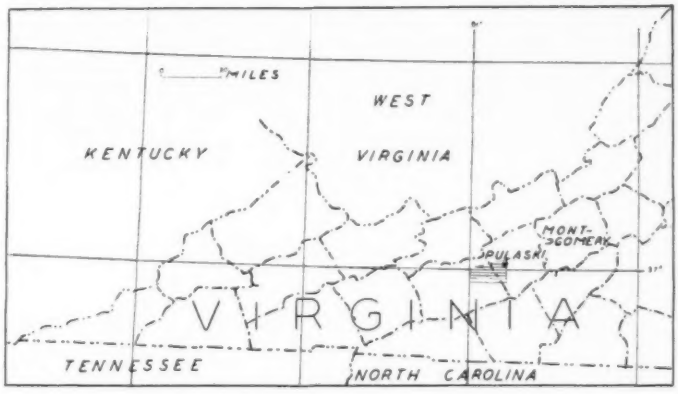

FIG. 1.—Index map showing location of Draper Mountain area

probably had in mind as the type locality some part of Montgomery County, Virginia. Campbell[3] later tried to revive the name "Montgomery," but, because no type locality had been designated and no stratigraphic definition of the beds had been made, it was deemed advisable to abandon the term. The present name "Price," which was introduced as the "Price sandstone" by Campbell,[4] was taken from Price Mountain, Montgomery County, Virginia. In 1925 he

[2] J. J. Stevenson, "A Geological Reconnaissance of Bland, Giles, Wythe, and Portions of Pulaski and Montgomery Counties, Virginia," *Proc. Amer. Phil. Soc.*, Vol. XXIV (1887), pp. 61–108.

[3] M. R. Campbell, "The Valley Coal Fields of Virginia," *Va. Geol. Surv. Bull. 25* (1925), pp. 24–25.

[4] M. R. Campbell, "Paleozoic Overlaps in Montgomery and Pulaski Counties, Virginia," *Geol. Soc. Amer. Bull. 5* (1894), p. 177.

discarded the specific lithologic designation and substituted the word "formation."

PREVIOUS WORK

Many descriptions of the Price have been published, but only a few discuss the stratigraphy in any detail. Papers by Campbell,[5] Branson,[6] Butts,[7] Stose,[8] and Woodward[9] have indicated features of Price stratigraphy in various portions of the Appalachian Valley in southwestern Virginia.

GENERAL DESCRIPTION

The Price formation is composed of a variety of sediments, but by far the most characteristic are coarse-grained, cross-bedded sandstones. For the most part this type of sandstone is micaceous and quartzose, but numerous beds of arkose are intercalated in the predominating type. The arkoses are readily distinguished on weathered surfaces by the presence of cream-colored blotches of weathered feldspar grains. The rocks are well cemented by iron oxide and quartz, and fresh surfaces are greenish gray to dark gray. Bleaching by weathering causes most of the exposures to appear whitish and saccharoidal. The finer-grained and more ferruginous layers weather to a highly rusty color which is very characteristic, and such layers contain an abundance of marine fossils. The cross-bedded structures in the coarse-grained sandstones and arkoses are abundantly developed. They are not to be confused with cross-lamination, which is

[5] M. R. Campbell, "Pocahontas Folio," *U.S. Geol. Surv. Folio 26* (1896), p. 3; "The Valley Coal Fields of Virginia," *loc. cit.*, pp. 23–28.

[6] E. B. Branson, "A Mississippian Delta," *Geol. Soc. Amer. Bull. 23* (1912), pp. 447–56.

[7] Charles Butts, "Oil and Gas Possibilities at Early Grove, Scott County, Virginia," *Va. Geol. Surv. Bull. 27* (1927), pp. 11–12; "Fensters in the Cumberland Overthrust Block in Southwestern Virginia," *Va. Geol. Surv. Bull. 28* (1927), p. 6; "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *Va. Geol. Surv. Bull. 42* (1933), pp. 36–37; "The Southern Appalachian Region," *Intl. Geol. Cong. Guidebook 3* (1932), p. 22.

[8] G. W. Stose, "The Pre-Pennsylvanian Rocks" in "The Geology and Mineral Resources of Wise County and the Coal-bearing Portion of Scott County, Virginia," *Va. Geol. Surv. Bull. 24* (1923), pp. 53–56.

[9] H. P. Woodward, "Geology and Mineral Resources of the Roanoke Area, Virginia," *Va. Geol. Surv. Bull. 34* (1932), pp. 66–68.

generally considered as developed within a single bed of rock. The cross-bedding of the Price consists of individual flaggy- to thick-bedded sandstone layers, all of which are beveled by beds above and below. The angular discordance of some of the beds is as high as 40°. Compensating for their present orientation, which is due in part to folding, the original dips of these "foreset beds" in a large number of exposures are inclined to the southeast, in the direction of the Piedmont crystalline area—the site of old Appalachia. Scattered through these beds are lenticular beds and lenses of quartz-

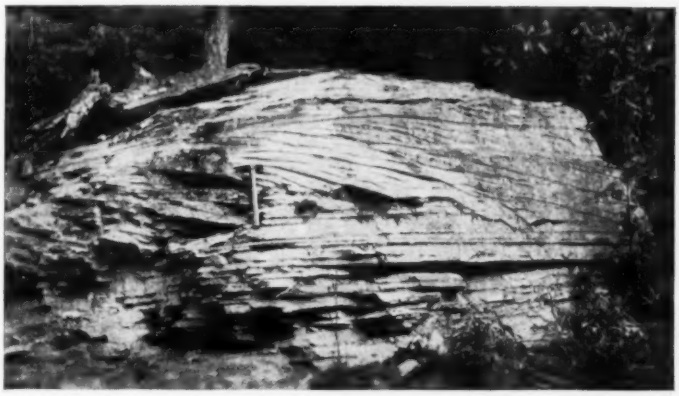

FIG. 2.—Cross-bedding in the Price as exposed along the road in the gorge of Miller Creek, north of Max Meadows, Virginia. The so-called "top-set" and "bottom-set" beds are essentially horizontal, but the "foresets" dip sharply toward the southeast.

pebble conglomerate, some of which attain a thickness of 10 feet. It is only in gorges cut through the ridges that the lenses can be seen in place.

The rocks described above, which represent the bulk of the Price above the coal beds, are approximately 400 feet thick. Between 200 and 300 feet of this type of clastic material also underlie the coal beds, and were it not for the intercalated coal, it would be difficult to subdivide the upper 800 feet of the Price. The type of lithology beneath the coal is well shown along the Lee Highway (U.S. Highway 11) just south of Calfee Park, south of Pulaski, Virginia. The best exposures of the cross-bedded sandstones above the coal are in

the gorge of Miller Creek in Little Brushy and Brushy mountains, north of Max Meadows, Virginia. Here they occur beneath the overlying red Maccrady formation in the northwest limb of an overturned and thrust-faulted syncline. The flaggy cross-bedding is well developed along the old stage road from Pulaski to Gunton Park, where that road begins the steep ascent to the crest of Caseknife Ridge, 2½ miles southwest of Pulaski.

Beneath the cross-bedded sandstone underlying the coal is a sequence of fine-grained, even-bedded, ferruginous sandstones, silt-

FIG. 3.—Blocky to thick-bedded strata characterized by uniformity and continuity of bedding. This type of lithology is characteristic of the lower 400 feet of the Price and of all of the underlying Chemung formation. Photograph taken near the contact of these formations.

stones, and shales about 400 feet thick. Most of the beds are highly fossiliferous. There are also a few beds of black shale, maroon-drab sandstone, quartzite, quartz conglomerate, and concretionary siltstone. The maroon-drab sandstone is very similar to beds occurring in the upper 200 feet of the Chemung formation.

The Price formation carries the geologically oldest coal beds mined in the United States. All the coal is semi-anthracite and occurs in irregular beds. There are three rather thick and persistent coal beds identifiable within the Draper Mountain area, which, together with associated thin coal lenses, clays, carbonaceous shales, and sand-

stones, form another distinct lithologic subdivision recognizable in this area. It is 75–100 feet thick. The lower coal bed, which is probably correlative with the Langhorne coal of adjacent areas, lies in most places on cross-bedded sandstone and is overlain by a characteristic bed of tough, gumbo-like clay which contains well-preserved plant fossils. The lower coal bed is the most uniform in thickness. In Cove Hollow, north of Max Meadows, on the Logdell Carwheel Company's property, a new prospect hole driven into the lower coal bed shows the presence of 5 feet 5 inches of good semi-anthracite. Approximately 18 feet above the Langhorne coal is another coal bed averaging about 4 feet in thickness. It is probably the partial equivalent of the Merrimac bed of Montgomery County. It is overlain in many places by a persistent stratum of black carbonaceous shale which contains excellent impressions of plants. This middle unit of coal and fossiliferous shale is exposed at the entrance of the old mine located at the side of the road in Miller Creek gorge, about 500 yards north of the forks of Miller Creek. About 40 feet above this coal bed is the third coal bed known locally as the "Gunton" coal. The rocks intervening between the Merrimac and the Gunton coals are micaceous, carbonaceous sandstones, clays, and shales. The Gunton coal is very irregular in thickness. In the vicinity of Gunton Park, 7 miles west of Pulaski on the Norfolk and Western Railway, it is reported to be in places nearly 10 feet thick. In Cove Hollow, west of the Miller Creek road, it is about 3 feet thick. The irregularity in thickness of the coal beds is probably primary in part, but also partly the result of compression during the Appalachian revolution by which the coal was squeezed out in some places and heaped up in others. It is difficult to distinguish the three beds in weathered exposures, for the coal disintegrates rapidly.

Red beds occur toward the top of the Price above the coarse-grained, cross-bedded sandstones overlying the coal. The overlying Maccrady formation is composed almost entirely of red or maroon mudrock, siltstone, and sandstone. The contact between the Price and the Maccrady is gradational and, because of the paucity of fossils, is more or less arbitrarily determined. The upper 25–35 feet of the cross-bedded sandstones overlying the coal are reddish. This material grades upward into finer-grained sandstone, siltstone, and

shale which are more reddish and more evenly bedded than the immediately underlying rocks. Many of the bedding surfaces of the red beds are mudcracked on a grand scale. Intercalated with these red rocks are thin horizons of fissile green siliceous shale. The upper boundary of the Price is best drawn where the red beds become predominately mudrock and sandy shale.

Generally recognized as marking the base of the Price formation is the so-called "Ingles" conglomerate, defined by Campbell[10] as the most distinctive "bed" in the formation. The name comes from Ingles Mountain, southwest of Radford, Virginia. The choice of the type locality was unfortunate, because there are no Mississippian rocks present in that vicinity. Butts[11] has shown that the "Ingles" conglomerate on Ingles Mountain is an outlier of the Clinch sandstone of Silurian age. The writer has seen a more or less persistent conglomerate horizon at the base of the Price at many localities in near-by areas, and at one locality on Cloyds Mountain, along the Dublin-Pearisburg road, the conglomerate together with intercalated cross-bedded sandstone is fully 75 feet thick. In the Draper Mountain area there is no persistent horizon of quartz conglomerate in the Price formation, but in several localities subordinate lenses of quartz conglomerate are intercalated in the shale and sandstone which comprise the lower 100 feet of the formation. These conglomerates are identical in character to conglomeratic lenses and lenticular beds occurring in the upper part of the formation. A horizon of quartz conglomerate, which is locally conspicuous, is exposed near the crest of Little Brushy Mountain, east of Miller Creek gorge, but this conglomerate is at least 50 feet above the base of the Price. The Chemung formation beneath the Price also contains lenticular beds of quartz conglomerate, but the matrix of these is much finer grained than is the quartz-sand matrix of the Price conglomerates.

The quartz conglomerate on Cloyds Mountain forms the basal part of the Price in that vicinity, but it is certain that there is no similar horizon at the base of the formation in the Draper Mountain area. On Cloyds Mountain the conglomerate is directly overlain by

[10] M. R. Campbell, "The Valley Coal Fields of Virginia," *loc. cit.*, pp. 26–28.

[11] Charles Butts, "Geologic Map of the Appalachian Valley of Virginia with Explanatory Text," *loc. cit.*, p. 36.

cross-bedded sandstone similar to that found below the coal near Pulaski. The absence of a sequence of fossiliferous beds above the Chemung and beneath the cross-bedded sandstone in the Cloyds Mountain section probably indicates either that the conglomerate zone at the base is partially equivalent to the lower 400 feet of fossiliferous beds of the Draper Mountain section or that it is younger than they are.

MEASURED SECTIONS

Knowledge of a formation as variable in lithology, both horizontally and vertically, as the Price can best be obtained from measured and described sections. The following measured sections vary in detail, because the lithologic units vary in thickness and because parts of the formation are so poorly exposed that it is impossible to obtain completely detailed sections.

TABLE 1*

SECTION OF THE LOWER PART OF THE PRICE FORMATION ALONG THE LEE HIGHWAY SOUTH OF CALFEE PARK, PULASKI, VIRGINIA

	Thickness	
	Feet	Inches
93. Black shale with bedding joints 6–12 inches apart; abundant plant fossils	4	6
92. Finely laminated black arkosic sandstone		6
91. Metallic-gray sandstone and siltstone		9
90. Gray arkosic siltstone peppered with plant fragments	2	9
89. Gray saccharoidal sandstone; plant fragment	2	
88. Black arkosic sandstone; plant fossils at base	1	
87. Ferruginous sandstone containing concretionary beds and thin seams of black shale with plant fossils	1	6
86. Thick-bedded, light-gray sandstone	5	
85. Lumpy greenish-gray siltstone and shale	3	3
84. Thin-bedded drab sandstone; plant fossils	3	
83. Blocky gray arkosic sandstone	5	9
82. Gray soft lumpy shale		6
81. Blocky arkosic sandstone	4	6
80. Gray to black lumpy shale		9
79. Gray clay and shale with intercallated 2-foot bed of coal which is locally pinched out	5	6

* Section begins 85 feet from the Lee Highway along the south drive of Calfee Park, at the base of the highest exposed coal bed.

	Thickness Feet	Inches
78. Interval mostly covered or slumped; contains brown siltstone, green lumpy shale, and a coal bed 1–5 feet thick	40	
77. Coal and intercalated bone (old mine)	6	
76. Coarse black to grayish-green flaggy cross-bedded sandstone and arkose	6	
75. Flaggy coarse-grained cross-bedded sandstone and conglomerate	2	6
74. Grayish-green shales with concretionary structures	9	
73. Flaggy cross-bedded arkose	7	
72. Thick-bedded, cross-bedded arkose	11	
71. Gray thin-bedded sandstone; few plant fragments	17	
70. Black quartzitic sandstone		3
69. Greenish sandstone with plant fragments	1	
68. Thin-bedded, cross-bedded, dark-gray sandstone	5	
67. Highly cross-bedded gray sandstone and arkose	2	
66. Medium-bedded, coarse-grained, quartzitic sandstone	10	
65. Black sandstone lenses in black shale	1	
64. Blocky olive-drab sandstone		6
63. Platy green shale		6
62. Finely laminated coarse-grained arkose containing lenses of black shale and clay ironstone concretions	4	
61. Black cross-bedded sandstone	14	
60. Gray lenticular to cross-bedded sandstone with stringers of black shale at the top	11	
59. Grayish sandstone containing nodules of clay ironstone	1	6
58. Platy olive-drab sandstone and shale		9
57. Mutually beveling beds of gray sandstone	1	6
56. Thick-bedded, cross-bedded, black standstone	5	
55. Platy black shale and thin-bedded sandstone	4	
54. Cross-bedded, coarse-grained, black sandstone	2	
53. Laminated beds composed of alternating sandstone and shale	3	
52. Blocky cross-bedded, black arkose		9
51. Greenish siltstone and shale	1	
50. Black sandstone containing nodules of glauconitic clay	1	6
49. Cross-laminated grayish-green shale	3	3
48. Blocky sandstone alternating with platy shale	3	
47. Black sandstone	3	
46. Platy black shale		3
45. Gray blocky sandstone		6
44. Platy black shale		3
43. Laminated gray arkose	3	3
42. Platy black shale		3

	Thickness Feet	Inches
41. Cross-bedded gray sandstone containing clay ironstone concretions	1	6
40. Black shale		3
39. Laminated ferruginous quartzite	1	6
38. Black shale and sandstone	2	9
37. Medium-bedded beveled layers of gray arkose	15	
36. Blocky quartz conglomerate in sheared zone	20	
35. Blocky sandstone and arkose	4	
34. Laminated shaly sandstone	15	
33. Blocky greenish-gray sandstone	1	6
32. Black shales intercalated in blocky gray sandstones	11	
31. Concretionary ferruginous sandstone	2	3
30. Cross-bedded gray sandstone	2	
29. Blackish siltstone with plant fragments		6
28. Black shale and thin-bedded black sandstone	7	
27. Quartz conglomerate	2	6
26. Thick-bedded gray arkosic sandstone	4	
25. Gray fracture-cleaved sandstone	22	
24. Blocky gray sandstone and shale	9	6
23. Black sandstone and shale	22	
22. Concretionary gray sandstone	1	
21. Thin-bedded calcareous sandstone and siltstone	9	
20. Blocky ferruginous sandstone, some of the beds concretionary, alternating with siliceous olive-drab shale	33	
19. Blocky yellowish-brown quartzite	3	6
18. Covered interval at culvert	9	
17. Blocky to thin-bedded arkosic sandstone and intercalated quartzite	10	
16. Greenish-gray sandstones interbedded with siliceous olive-drab shale	30	
15. Olive-drab siliceous shale with iron oxide fretwork along strike joints	4	
14. Olive-drab siltstone and sandstone interbedded with siliceous olive-drab shale	40	
13. Interbedded tan and gray shale	10	
12. Thin-bedded olive-drab sandstone	5	
11. Olive-drab sandstone and shale	37	
10. Blocky ferruginous sandstone	8	
9. Concretionary sandstone	4	
8. Greenish platy sandstone and shale	55	
7. Dark-gray to black siliceous shale	10	
6. Slumped interval composed of thin-bedded olive-drab sandstone, siltstone, and shale	15	

	Thickness Feet	Inches
5. Blocky gray sandstone and intercalated lenses of quartz conglomerate	15	
4. Flaggy olive-drab sandstone and shale	8	
3. Gray resistant sandstone, weathering purplish, and interbedded gray shales	25	
2. Thin-bedded to blocky sandstone and olive-drab shale, containing a few purplish sandstone beds	30	
1. Fine-grained sandstone in blocky beds. Contains flaggy beds which are grayish-white on weathered surfaces but reddish on fresh surfaces†	18	
Total thickness of foregoing section	740±	

Chemung-Price contact.

† Nos. 1–28 contain marine fossils.

TABLE 2

SECTION OF THE UPPER PART OF THE PRICE FORMATION ABOVE THE COAL BEDS IN THE GORGE OF MILLER CREEK IN LITTLE BRUSHY MOUNTAIN, NORTH OF MAX MEADOWS, VIRGINIA*

	Thickness Feet
Price-Maccrady contact.	
Price formation	
6. Reddish to deep-maroon fine-grained sandstones and shales, soft and lumpy toward the top. Minor intercalations of siliceous green shale. Bedding surfaces mudcracked	30
5. Cross-bedded gray micaceous sandstones and arkoses with intercalated lenses of quartz conglomerate	50
4. Thick-bedded sandstone and arkose in beds 1–12 feet thick. Finely cross-laminated. *Taonurus* markings common on bedding surfaces	135
3. Thick-bedded, cross-bedded whitish micaceous quartz sandstone and gray arkose with some quartzitic layers. Bedding very lenticular. Discordance of some of the beds as high as 40°. Interbedded lenses of quartz conglomerate, the pebbles of which are not more than 1 inch in diameter; matrix either quartzite or arkose. *Taonurus* common	175
2. Punky ocherous shale and mealy siltstone intercalated with olive-drab micaceous sandstone	25
1. Upper coal bed	5
Total thickness of foregoing section	420±

* The striking cross-bedded and lenticular character of the rocks above the coal and the lack of continuity of exposures prevent accurate measurement of the various units described.

TABLE 3

CONSOLIDATED DESCRIPTION OF THE PRICE FORMATION IN THE DRAPER MOUNTAIN AREA*

	Thickness Feet
Maccrady formation.	
Price formation.	
6. Reddish shale and fine-grained sandstone	30
5. Strikingly cross-bedded quartz sandstone, arkose, and lenses of quartz-pebble conglomerate. Minor proportions of more even-bedded sandstone and arkose	350
4. Ferruginous micaceous sandstone and shale	25
3. Coal beds and associated sandstones, shales, siltstones, and clays	70
2. Cross-bedded sandstone and arkose with intercalated lenses of quartz conglomerate	300
1. Fine-grained gray to brownish ferruginous sandstone, olive-drab shale, and quartz conglomerate. Contains abundant marine fossils	450
Total thickness of Price formation	1,250±
Chemung formation.	

*The major lithologic subdivisions of the Price are indicated by the following condensation of the foregoing sections.

FOSSILS

The lower 400 feet of the Price formation in the Draper Mountain area contain an abundance of marine fossils, some of which are present in nearly every bed. Campbell[12] noted "the presence here and there of marine fossil shells," but he failed to note that in some localities, such as the Draper Mountain area, fossils are abundant throughout the lower third of the formation. Holden and Reger[13] collected fossils below the coal beds, out of Reger's "Broad Ford sandstone" in the vicinity of Poverty Gap, in Montgomery County, Virginia. Butts[14] has collected fossils from the Price at many localities in the southern Appalachian region. Miller[15] has described a

[12] M. R. Campbell, "The Valley Coal Fields of Virginia," *loc. cit.*, p. 24.

[13] D. B. Reger, "Mercer, Monroe, and Summers Counties," *Bull. W. Va. Geol. Surv.* (1926), pp. 520–25.

[14] Charles Butts, "Oil and Gas Possibilities at Early Grove, Scott County, Virginia," *loc. cit.*, pp. 11–12.

[15] A. K. Miller, "A Mississippian Goniatite from Virginia," *Jour. Paleon.*, Vol. X (1936), pp. 69–72.

single specimen of a goniatite from the Price and has listed its faunal associates as collected and identified by Butts. No fossil lists have been published based on collections in the Draper Mountain area. The writer collected the following forms from the Draper Mountain section of the lower Price of this area:

Lepidodendron scobiniforme Meek
Triphyllopteris lescuriana Meek ?
Lingulodiscina (Oehlertella) pleurites Meek
Orthotetes crenistria (Phillips?)
Chonetes (cf. *C. scitulus* Hall)
Chonetes sp.
C. illinoisensis Worthen ?
Camarotoechia sappho Hall
C. contracta Hall ?
C. marshallensis Winchell
Leptodesma (cf. *L. propinquum* Hall)
Leptodesma (cf. *L. truncatum* Hall)
Romingerina julia (Winchell)
Spiriferina (cf. *S. depressa* Herrick)
Athyris ohioensis Winchell
Sphenotus flavius (Herrick)
Grammysia sp.
Edmondia sp.
Leda sp.
Cryptonella eudora (Hall)
Schizodus sp.
Allorisma consanguinatum Herrick
Allorisma sp.
Cypricardella bellistriata Conrad
Bellerophon (cf. *B. helena* Hall)
Tropidodiscus cyrtolites (Hall)
Euphemus galericulatus (Winchell)
Straparollus sp.
Othoceras indianiense Hall
Münsteroceras sp.
Taonurus sp.

Above the thick-bedded gray sandstone carrying *Productella hirsuta, P. lachrymosa, Spirifer mesicostalis,* and *Orthotetes chemungensis,* at the top of the Chemung formation, abundant representatives of species of *Camarotoechia* and *Chonetes* are almost the only fossils to be found in the lower 30–50 feet of the Price. About 50 feet above the base a single *Spiriferina* was found, besides the common genera previously mentioned. Above this horizon a larger variety of fossils occurs in great abundance. Just north of the first road culvert on the Lee Highway ascending Draper Mountain, the entire fauna listed above can be found in a few feet of beds. The fossils decrease in variety above this point, but *Chonetes* and *Camarotoechia* persist upward to the black shale which underlies the lower zone of cross-bedded sandstone. In the black shale *Grammysia* and *Allorisma* are common. Above this horizon the only animal fossil found was *Taonurus.* Plant fossils are abundant in the coal-bearing portion. A variety of the latter fossils can be collected from shale beds exposed along the road paralleling Valley Branch, just northeast of

an old coal-mine dump, 1 mile southwest of Pulaski. Another exposure of this shale is located along the south drive of Calfee Park near its junction with the Lee Highway. Probably quite a variety of undescribed species is present in these shales, but most of the fossils collected by the writer are referable to *Lepidodendron scobiniforme* Meek.

AGE AND CORRELATION

The Price formation, as indicated by the foregoing fauna, is the approximate stratigraphic equivalent of the New Providence formation of Indiana and Kentucky, which is Lower Osage in age. The diagnostic *Euphemus galericulatus* is considered by Butts to be proof of this correlation. The *Taonurus* which occurs in the Price is common in the New Providence and Price formations along the Allegheny Front and in eastern Kentucky and Ohio as well. The occurrence of this fossil in the Esopus grit and Oriskany sandstone of New York and Pennsylvania is well known, but possibly the Price and Oriskany-Esopus occurrences are of different species. Apparently this fact has not been established. Its recurrence in the Mississippian in rocks of New Providence age in the eastern half of the United States has been the basis of many correlations—most of which are now accepted as correct in the light of additional faunal evidence. The fauna contains many species common in the Cuyahoga formation of the Waverly group of Ohio. The presence of *Münsteroceras*, common in the Rockford formation of Indiana, might be taken to indicate that the Price, at least in part, might be Kinderhookian in age. However, Miller[16] has described several forms of goniatites, including species of this genus from the Burlington of Iowa, whose Osage age is not questioned. According to Butts,[17] the Cuyahoga connects stratigraphically with the New Providence at Portsmouth, Ohio, and is continuous with the Pocono of Pennsylvania. The Price and the Pocono are essentially the same stratigraphic unit, and both names are used in Virginia. The term "Price" is reserved for rocks of New Providence age south of James River, and Pocono is used north of that more or less arbitrary line. The Price formation

[16] A. K. Miller, "Burlington Goniatites," *Amer. Jour. Sci.*, 5th ser., Vol. XXX (1935), pp. 432–37.

[17] A. K. Miller, "A Mississippian Goniatite from Virginia," *loc. cit.*, pp. 71–72.

of the Draper Mountain area probably represents a near-to-shore facies of the New Providence formation of the Cumberland-Allegheny plateau region. It is the approximate equivalent of the Burlington limestone of Iowa.

There is some lithologic evidence that the so-called "Ingles," as it occurs on Cloyds Mountain, is roughly the equivalent of the Berea grit of Ohio, which connects with the Knapp sandstone of Pennsylvania. Reger states:

> In Montgomery County, Virginia, the base of the Price (Pocono) Formation is made by a conspicuous white, quartz conglomerate, described as the "Ingles Conglomerate" by Campbell and others, the identity of which with the Berea Sandstone is not much in doubt, since it occurs just over the fossiliferous Chemung and only about 200 feet below the Broad Ford Sandstone.[18]

If the so-called "Ingles" is equivalent to the Berea and therefore Kinderhook in age, the conglomerate on Cloyds Mountain is older than the oldest Price in the Draper Mountain area. It would seem more likely that the conglomerate on Cloyds Mountain is equivalent to some one or more of the similar but less well-developed conglomerates within the Price of the Draper Mountain area. The close association and intercalation of the conglomerate on Cloyds Mountain with cross-bedded sandstone would strongly suggest that in that locality, at least, the so-called "Ingles" is younger than the lower 400 feet of the Price formation of the Draper Mountain area, and therefore of New Providence age also. Until additional fossil evidence proves otherwise, it seems best to consider that all the Kinderhook is absent by unconformity in the Draper Mountain and adjacent areas.

SEDIMENTARY ENVIRONMENT

That the lower 400 feet of the Price formation are marine seems evident from the foregoing paleontological and lithological facts, but the environment of deposition of the other part of the Price is not so easily determined. The apparent paucity of marine fossils and the local abundance of plant remains and coal indicate that the upper 850 feet of the Price were deposited under very different conditions from the lower 400 feet. Lenticular bedding, paucity or absence of marine fossils, the striking cross-bedding, the coarse grain of the

[18] Reger, *op. cit.*, p. 531.

sandstones, and the presence of coal beds—all have been cited as strongly indicative of continental origin.

Campbell bases his belief in a subaerial origin upon the following facts:

> . . . . but few of the beds are continuous for any great distance, showing that the material composing them was brought to its position by streams flowing on the land, and that while sand was being laid down in one place mud was being deposited in another.[19]

Branson states his belief in a subaerial origin as follows: "The presence of coal, the absence of marine fossils, and the character of the sediments indicate a subaerial and fresh water origin."[20] Later in the same paper he states: "During Mississippian time the region of Cloyds Mountain (northwest of the Draper Mountain area), Virginia, was part of a great delta and was generally the site of subaerial deposition."[21]

The interpretation of the coal beds and immediately associated rocks as continental in origin seems justified by our present knowledge of the conditions under which peat deposits accumulate. This is no indication that the cross-bedded sandstones above and below the coal are subaerial deposits.

Modern investigations of sedimentation have made it necessary to revise completely criteria for distinguishing continental and marine deposits. Lenticular bedding is indicative of no specific environment of deposition, and cross-bedding, even of the so-called "deltaic" type, is suggestive merely of rapidly changing conditions of erosion, transportation, and deposition within any one of several environments. Coal intercalated in sandstone gives no indication of the origin of the sandstone; for in many places, particularly in the Pennsylvanian system, persistent coal beds are overlain by marine rocks. Hence, the evidence cited as a basis for a nonmarine origin of the Price is not conclusive.

The Price sandstones are very similar to other sandstones whose marine origin is not questioned. They differ from the others merely in being arkosic and strikingly cross-bedded. The grains of the sand-

[19] M. R. Campbell, "The Valley Coal Fields of Virginia," *loc. cit.*, pp. 25–26.

[20] Branson, *op. cit.*, pp. 450–51.

[21] *Ibid.*, pp. 454–55.

stones and arkoses are well sorted and well washed. The grains and pebbles of the quartz sandstones and conglomerates are flattish and rounded. Uniformity of grain and constituent material, the high degrees of rounding, the flattish shapes of the fragments in many places, and the concentration and sorting of heavy accessory minerals —all suggest features of marine deposits. It is evident that these sandstones were deposited after long and vigorous washing and sorting by wave action.

The writer for a time considered the cross-bedding of the sandstones to be fair evidence of continental origin. In the course of his observations, however, he noticed that a large part of the "foreset beds" must have had an original dip to the south and southeast. If the sands were river deposits, this would indicate either that the southeastwardly inclined "foresets" were an antidune phase of channel deposition or that they were channel or flood-plain deposits made by a meandering stream that flowed in parts of its course toward the southeast. Marine sands usually exhibit cross-bedding inclined in toward the land as well as toward the sea. The association of quartz-pebble conglomerate lenses with the sandstones at many horizons, which vary in their stratigraphic positions from one locality to another, might well be taken as an indication of marine origin. The conglomerates can be interpreted as representing well-washed and well-sorted gravels of the beach zone which occasionally were eroded and transported seaward to be deposited on the sands accumulating farther out in the littoral zone. The vigorous conditions of erosion, transportation, and deposition within the beach zone and the variability of competency of marine waves and currents are such that material accumulating therein is typically cross-bedded, with the cross-bedding inclined in all directions, and is well sorted and rounded.

Lenticularity is a common feature of Price beds, but it is also characteristic of the beds of most other Appalachian formations. Even the Cambrian-Ordovician limestones of this general region are lenticularly bedded. Lateral variation in lithology of individual beds is common in most clastic deposits in this province, including the Price formation. Variation in thickness of the Price has been noted by previous workers, particularly Branson, as indicative of deltaic

conditions of sedimentation. It is evident that this fact alone is not a valid criterion because, in most cases, the thinning and thickening of the Price are in hundreds of feet, whereas some marine deposits in the southern Appalachian region are known to vary thousands of feet in thickness within short distances. An example of the latter is the variation in thickness of the Blount group in Virginia and Tennessee.[22]

Taonurus is common in the typically marine Price of southwest Virginia and still more common in the New Providence of eastern Kentucky. The writer believes that the presence of this fossil in the cross-bedded sandstones of the Price formation in the Draper Mountain area is further indication of the marine origin of these beds.

[22] Charles Butts, "Variations in Appalachian Stratigraphy," *Jour. Wash. Acad. Sci.*, Vol. XVIII (1928), pp. 357–80.

DRAINAGE LINES IN BAS-RELIEF[1]

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ABSTRACT

Old drainage lines in bas-relief have been found in Nejd, Eastern Saudi Aarbia, south of Darb Zubaida, 350–400 kilometers west of the Persian Gulf. There had been developed a hard caliche in this area. On this caliche surface a dendritic drainage pattern was formed. Wind, assisted by leaching action of waters, has scooped out hollows and eroded between the tributaries leaving old stream beds as tops of hills and ridges (Fig. 1). Such a fossil drainage may be called "suspendritic."

While doing geological reconnaissance work by airplane in Eastern Saudi Arabia, the writer observed a "fossil" type of old drainage lines which, so far as known to him, has not been described as existing elsewhere. The appearance of the drainage lines as viewed from the air can be compared to the optical illusion which often appears when viewing airplane vertical photographs under incorrect lighting, i.e., the hills appear as valleys and the valleys as ridges. Actually, the apparent stream courses *are* the tops of ridges and hills, and they are frequently more than 12 meters above their surroundings. They are only conspicuous from an elevated position, such as a plane flying over the area. Viewed from the air they present in bas-relief a remarkable dendritic pattern (Fig. 2).

These features are to be found in a roughly rectangular strip—more than 10,000 square kilometers in area—in Nejd, 350–400 kilometers west of the Persian Gulf, south of Darb Zubaida, and east of the Dahana. The present, as well as earlier, drainage over the greater part of this area is eastward. The amount of rainfall each year, often torrential in type, is not great, generally being only a few inches.

The airplane pictures of the region show the rough nature of the topography. Relief is very low, being seldom above 15 meters.

A caliche formation, as a rule less than 3 meters thick, caps the hills and ridges in this region. It is a hard formation composed of gray

[1] Published with the permission of Mr. G. C. Gester, chief geologist of the Standard Oil Co. of California, to whom and to Dr. A. O. Woodford acknowledgment is made for constructive criticism.

and tan, often mottled, limestones, sandstones, sandy limestones, and recemented breccias. Less commonly the color is reddish brown developed on hard, calcareous sandstones and conglomerates. Cherts are common and are the result of replacement. More commonly the caliche cement is calcium carbonate, either filling the pores of the local rock or binding together angular blocks of varying size.

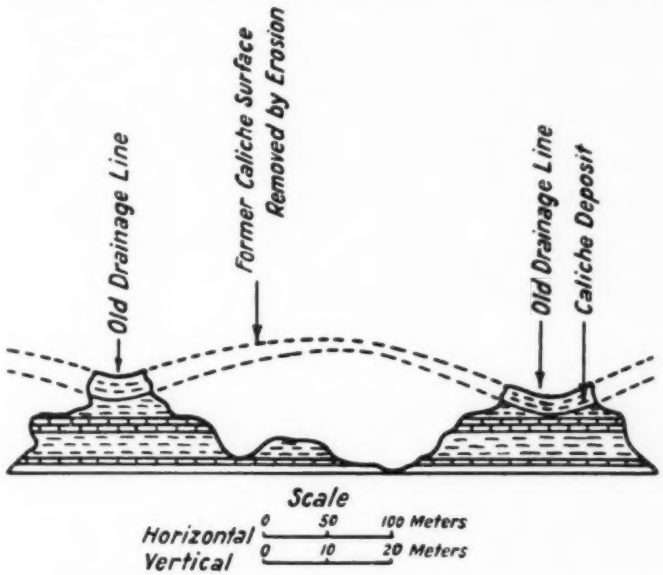

FIG. 1.—Ideal section. Profile across two drainage lines in bas-relief. It shows the old caliche surface in dotted lines before being removed by erosion. The present surface is shown in full lines.

In the caliche formation peculiar minor structures are developed, some resembling corals. In some places these are so abundant as to look like extensive coral reefs. In other places columnar structure appears. Laminae which vary in attitude from vertical to horizontal are common. The laminae are formed along bedding planes, joints, etc. As in most caliche deposits pseudo-bedding planes often parallel the land surface so that members appear to dip toward the shallow depressions of the old stream beds.

Apparently the caliche is still forming at the present time. Water after rains flows strongest in the drainage channels, and moisture remains longest beneath them. It seems that the caliche is more tightly cemented and is thicker in these places. Owing to the widespread areal distribution of the caliche throughout the more or less flat region known as the Summan, this name has been given the formation.

FIG. 2.—Oblique picture looking toward the south. White at the right top of the picture is the sands of Ed Dahana. The picture clearly shows the bas drainage lines. The white line is in the old bas stream course. Note in the lower right-hand corner the severed stream course. It is not clear with which branch of the main stream it joined, but there is some evidence that it flowed eastward.

The white rounded areas are hollows scooped by wind and leached out in the members below the hard caliche formation. The streamlined effect of wind-eroded hills is not clearly shown but may be seen with a little inspection.

The Summan covers all older formations, but in the region under discussion it caps shales, pure limestones, marly limestones, pure white chalks, and chalky limestones, many of which are porous and powdery owing to leaching. Erosion of the Summan formation prob-

ably had its beginning at the highest points along the interdrainage lines. Wind was the chief erosive agent. After part of the cap rock had been removed, erosion was accelerated by the leaching action of rain water, soaking where it fell into the older rocks, so that material was loosened for removal by the winds. Undermining of the Summan formation and the development of caves and sinks occurred extensively. As a result of wind erosion and leaching action prominent hollows with escarp-like rims have been formed between the old drainage lines. The effectiveness of the wind action is clearly shown by the shape of the hills in most of the pictures accompanying these notes. The hills are streamlined with the blunt ends heading into the prevailing wind which is from the north-northwest (Fig. 3).

The origin of the present bas-relief dendritic pattern may be explained thus: Water ran in greater volume and for longer periods in the stream channels than in the interchannel areas. As a result, more water sank into the rocks underlying the channels than in the areas between the stream courses. Caliche deposits being due to the evaporation of ground water drawn to the surface by capillarity and the precipitation of solutes,[2] deposition of this material was greatest in the drainage lines, where most water was available for capillary action and precipitation. Cementation of grains, etc., being greatest where there was the most water, the surface rocks along the drainage lines became more indurated and more resistant to weathering than those of neighboring areas. Consequently, erosion has removed the Summan formation and underlying rocks from between the drainage lines, leaving the harder Summan formations of the former stream courses eventually as ridges and hills. The original dendritic pattern was preserved as clearly shown by the prints (Fig. 4).

In places new stream courses are being developed beside the older, and the elevated old courses in many places have become severed from the former main drainage lines (Fig. 2). All stages of erosion of the old pattern exist; in some cases only a portion of the old main trunks remains. Some of the old stream channels enter, without abrupt change of gradient, into basins which also receive waters from younger drainage.

[2] W. H. Twenhofel, *Treatise on Sedimentation* (2d ed., 1932), p. 479.

FIG. 3.—Oblique picture showing how erosion has removed much of the old bas drainage lines. The streamlining of the hills, buttes, and ridges is clearly shown. The prevailing wind direction is from the north-northwest.

FIG. 4.—Oblique picture looking toward the south. The bas drainage lines are more clearly shown than in Figure 2. Note the effect of wind erosion.

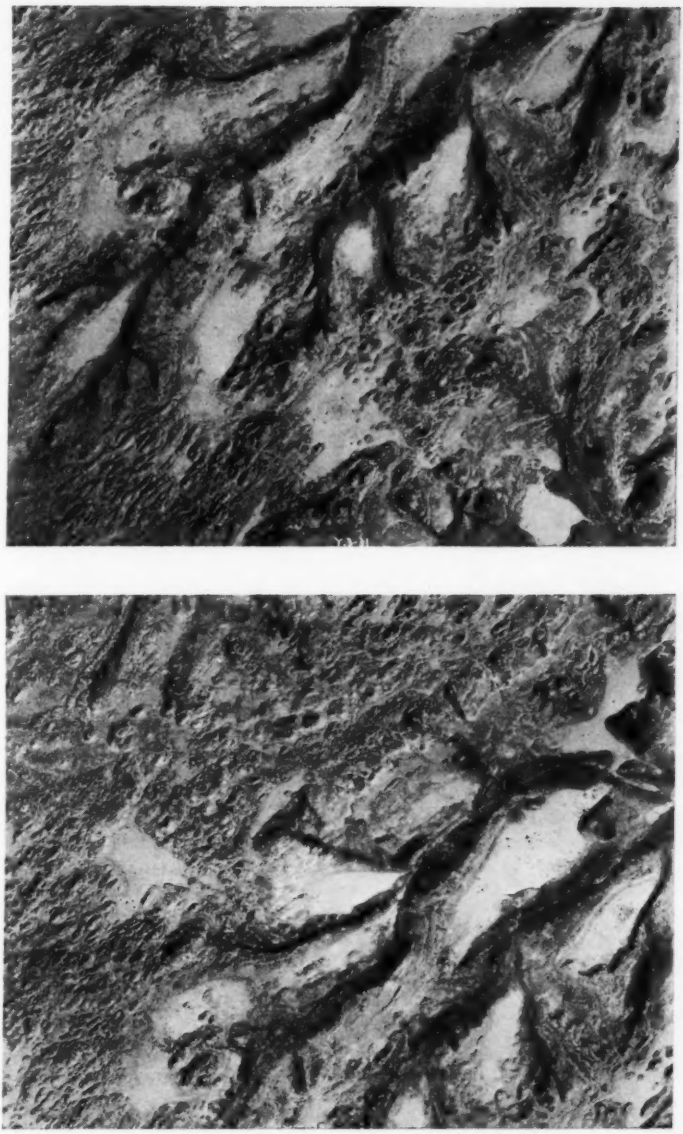

FIG. 5.—Vertical pictures which are part of a strip taken when flying above a bas stream course. The hollows formed by leaching and wind erosion between the old streams are plainly shown. These pictures are interesting when studied under a stereoscope.

The elevated drainage pattern described is characteristic for this region and to the writer's knowledge has not been described as existing elsewhere.[3] This type, however, may be found elsewhere when more country is examined from the air. It seems to deserve a special name. Following the custom of geomorphologists, the descriptive phrase "suspended dendritic drainage" may be telescoped

FIG. 6.—Vertical picture showing broken bas drainage lines. A little inspection shows that the wind direction is from the lower left corner. Note the group of small streamlined hills in the lower middle section appearing as if headed into a stream. In some areas large numbers of these are grouped together and have the same general appearance as this small group.

to "suspendritic drainage" as the name for the features here described.[4] The term "suspended drainage" is suggested for any portion of a drainage system preserved in relief.

[3] A rudimentary and doubtful case has been described from the Mojave Desert of southern California (A. O. Woodford and T. F. Harriss, *Univ. Calif. Publ. in Geol., Bull. 17* [1928], pp. 282, 289).

[4] Of course, the channels are not literally suspended, but neither are "hanging valleys" literally hanging.

OSTEOLOGY OF *BYSMACHELYS CANYONENSIS* A NEW TURTLE FROM THE PLIOCENE OF TEXAS

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ABSTRACT

This paper presents a new genus of land turtles from the Upper Pliocene of West Texas. The almost complete skeleton is described, measurements given, and diagnostic characters pointed out.

INTRODUCTION

The specimen to be described in this paper is the almost complete skeleton of a large land turtle (*Bysmachelys canyonensis* gen. et sp. nov., Panhandle Plains Historical Mus. No. 1534) found articulated in a coarse, brown sand of Upper Pliocene age. The type locality is in the center of the west half of Sec. 164, Block 6, Randall County, Texas, where the sand outcrops in the bluffs and cliffs of North Cita Canyon, a branch of the Palo Duro Canyon, and is overlain and underlain by fossil-bearing strata which are also of Upper Pliocene age. In general character these sediments are very similar to the Upper Pliocene of Mount Blanco in Crosby County, Texas. The old river-bed deposits are in both instances typical of many similar deposits to be found in the High Plains region as described by Gidley in 1903.[1] However, the vertebrates so abundant in the upper and lower beds are not found in the intermediate brown-sand stratum in which thus far only turtles have been discovered. These beds and the Upper Pliocene fauna that they contain will be discussed in a forthcoming publication.

DESCRIPTION OF MATERIAL

In the following description and discussion the distinguishing characteristics of this type specimen of a new genus and species will be brought out, and taxonomic relationships and differences made clear.

[1] J. W. Gidley, "The Fresh-Water Tertiary of Northwestern Texas," *Bull. Amer. Mus. Nat. Hist.*, Vol. XIX, Art. XXVI (1903).

THE SKULL

The skull (Figs. 1 and 2) is complete with the mandibles, and there is but slight distortion which can be seen in the region of the pterygoids and the zygomatic arches. This causes an error in measurement of the length between the occipital condyle and the premaxilla of approximately 5 mm. but does not seem to affect the measurement between the anterior end of the prefrontals and the supraoccipital. In other words, the distortion has had the effect of

TABLE 1

MEASUREMENTS OF SKULL

	Mm.
Total length of skull anterior end of prefrontals to posterior end of supraoccipital	118
Length measured from anterior end of premaxilla to occipital condyle	124
Width at the quadrates	129
Interorbital space	50
Width of palatal fossa	52
Length of mandible	85
Depth of mandible at the symphesis	19
Greatest diameter of orbit	36
Diameter of orbit at right angles to greatest diameter	20
Breadth of condyle	13
Height of foramen magnum	15
Breadth across the external nares	44
Depth of skull anterior to orbits	59
Depth of skull at quadrates	50
Breadth of cranium opposite the vacuities	33
Breadth of palatal shelf	19

bringing the maxilla and premaxilla downward and backward in the direction of the quadrates.

It will be noted from the foregoing measurements that the skull is unusually broad in proportion to its length, the ratio of the width to length being 104 per cent as compared to *Testudo impensa* in which the ratio is 70.2 per cent; in *T. orthopygia* it is 72 per cent; and in *T. osborniana*, 68 per cent.

THE PECTORAL GIRDLE

The pectoral girdle (Fig. 3) is complete and undistorted. The elements are strong and so constructed as to constitute a rigid

Fig. 1

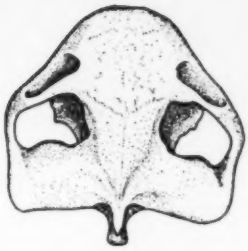

Fig. 2

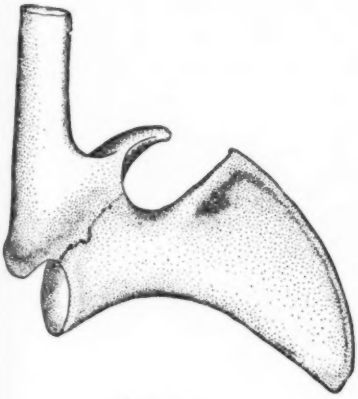

Fig. 3

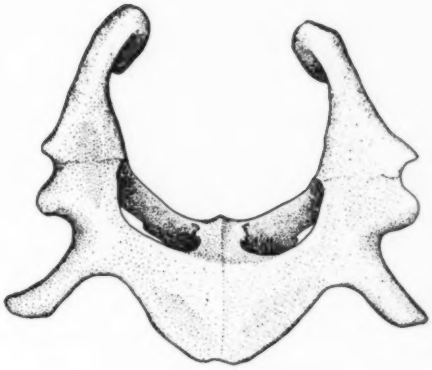

Fig. 4

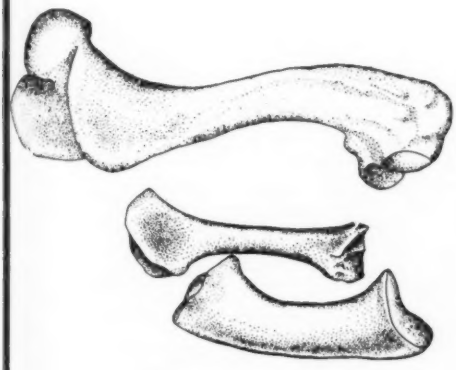

Fig. 5

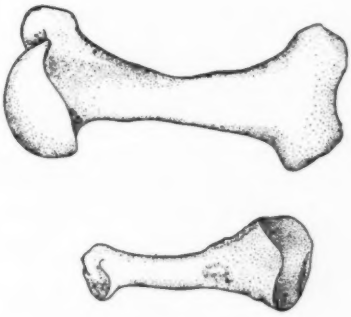

Fig. 6

FIGS. 1–6.—*Bysmachelys canyonensis*, gen. et sp. nov. FIG. 1, side view of skull. ×0.3; FIG. 2, dorsal view of skull. ×0.3; FIG. 3, dorsal view of left side of pectoral girdle. ×0.3; FIG. 4, anterior view of pelvic girdle. ×0.3; FIG. 5, humerus, radius, and ulna. ×0.3; FIG. 6, femur and tibia. ×0.3.

supporting member between the carapace and the plastron. The dorsal and ventral portions of the scapula are broad, strong, and round to elliptical in cross section, while the coracoid to which the scapula is solidly ankylosed is broad, thin, and fan-shaped.

TABLE 2

MEASUREMENTS OF THE PECTORAL GIRDLE

	Mm.
Length of scapula from center of glenoid cavity to dorsal extremity	145
Diameter of scapula 6 cm. below dorsal extremity	29
Length of ventral blade of scapula from center of glenoid cavity	133
Length of coracoid from ventral margin of glenoid cavity to posterior extremity	165
Greatest breadth of coracoid	155
Narrowest diameter of coracoid	42
Diameter of glenoid cavity	58

THE PELVIC GIRDLE

There appears to be no distortion in the pelvis (Fig. 4); and the bones are all solidly ankylosed into a single unit which is thickest and strongest in the region of the acetabulum.

TABLE 3

MEASUREMENTS OF THE PELVIC GIRDLE

	Mm.
Vertical height of pelvis when resting in a normal position	205
Anterior edge of symphesis pubis to posterior margin of ischium on the midline	162
Width between exterior margins of pubis	237
Anteroposterior diameter of ischiopubic fenestra	62
Transverse diameter	63
Length of illium dorsal to center of acetabulum	127
Breadth of pelvis across the margins of the acetabulae	269
Greatest diameter of acetabulum	63
Diameter transverse to above	49

THE LIMBS

The humerus and femur.—The length of humerus (Fig. 5) from proximal extremity of head to distal end is 229 mm. The length of

femur (Fig. 6) from proximal extremity of head to extremity of distal end is 169 mm. The ratio of length of femur to length of humerus is 73 per cent. In *Testudo orthopygia* this ratio is 75 per cent. In *Gopherus polyphemus* it is 74 per cent. The humerus is a stout bone with but little curvature. The diameter of the head is 47 mm. The anteroposterior diameter of the shaft in the midsection is 30 mm. Maximum width across the distal end is 94 mm. Maximum thickness of the great trochanter is 30 mm. Greatest width of head of femur is 58 mm.; greatest width at the distal end, 73 mm. Anteroposterior diameter of shaft at the midsection is 29 mm. There is a sharp ridge on the distal end which definitely marks the separation of the articular surface for the tibia and fibula.

The tibia.—Width across the distal end of the tibia (Fig. 6) is 31 mm.; greatest diameter of the shaft at the midsection, 19 mm.; proximal, transverse breadth of tibia, 46 mm.; anteroposterior breadth, 40 mm. Total length of tibia is 113 mm. This is a very stout bone proximally and as may be seen from the measurements it tapers rapidly to the distal end, being marked by numerous rugosities and muscle attachments.

The fibula.—This bone (Fig. 7) is slender and slightly curved in the middle, being larger distally than proximally. Length is 103 mm.; transverse diameter of distal end, 29 mm.; anteroposterior diameter, 24 mm. The greatest diameter of shaft at midsection is 14 mm.; greatest diameter at proximal end, 20 mm.

The ulna.—This is a strong bone (Fig. 5), somewhat curved and more or less wedge-shaped in cross section. Length is 135 mm.; transverse diameter at proximal end, 35 mm.; anteroposterior diameter at this end, 50 mm. Greatest diameter of shaft at midsection is 28 mm.; transverse diameter at distal end, 19 mm.; anteroposterior diameter at this end, 46 mm.

The radius.—This is relatively longer than the ulna, more slender in build, and tends to be more slender in cross section (Fig. 5). At the distal end it widens into a thick, flat, bladelike extremity. At the proximal end it widens into a broad, concave, semicircular articular surface. Length is 129 mm.; greatest diameter at the proximal end, 40 mm. Transverse diameter at this end is 30 mm.;

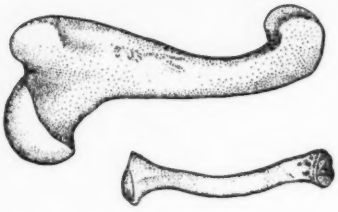

Fig. 7

Fig. 8

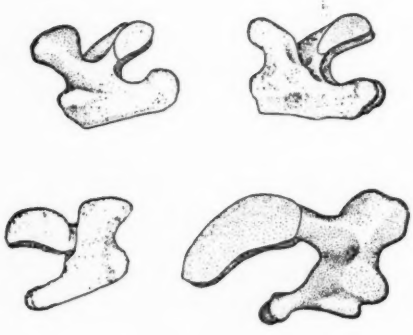

Fig. 9

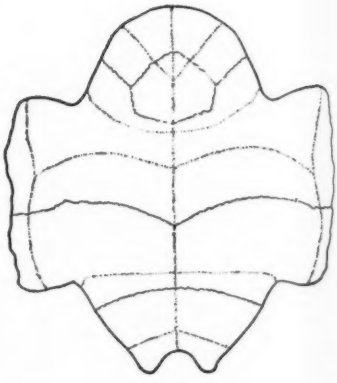

Fig. 10

FIGS. 7–10.—*Bysmachelys canyonensis*, gen. et sp. nov. FIG. 7, side view of femur and fibula, ×0.3; FIGS. 8 and 9, cervical vertebrae, ×0.3; FIG. 10, ventral view of plastron, ×0.0685.

greatest diameter of shaft at midsection, 16 mm. Transverse diameter at distal end is 18 mm.; greatest diameter at distal end, 44 mm.

The pes.—While all the feet were not found complete, a number of bones of each was found in an articulated position, the right front and the right rear being most nearly complete. In the right front foot four ungual phalanges were found. They are short, broad, and heavy, and more or less spatulate in shape. They vary in length from 43 to 46 mm., in width from 21 to 27 mm., and in thickness from 17 to 24 mm. The phalanges proximal to these are 10 mm. and less in length, and the carpals and tarsals are likewise shortened and compressed. Thus the foot must have been very short, stubby, and elephant-like in general appearance.

The bones of the hind foot have about the same general proportions as those of the front. The phalanges, with the exception of the ungual phalanges, are very short. These latter, however, are similar to those just described. A few round, flat dermal ossicles were found associated with the feet. These averaged about 20 mm. in diameter.

THE VERTEBRAE

Cervical vertebrae.—The cervical vertebrae (Figs. 8 and 9) are large, broad, and strong. They are eight in number and have a combined length of 335 mm. The atlas and axis, although not figured, were present.

Dorsal vertebrae.—As the dorsals enter into the structure of the carapace, a large part of which was lost, not much can be said of them except that they are slender and elongate.

Caudal vertebrae.—Most of the caudals were preserved, and it is estimated that the tail did not exceed 20 cm. in length. These vertebrae are short and relatively broad. There was, however, no indication that dermal ossicles were present in this region as is true in some other members of the Testudinidae.

THE PLASTRON

The plastron (Fig. 10) has a total length of 805 mm. Width of plastron along suture between the hyo- and hypoplastra is 545 mm. The anterior end of the plastron is round, with no sign whatsoever of a notch or projections. Indeed, if the sulcae between the gular and

humeral scutes be taken as radii with their intersection as the center of a circle, the arc described by them would coincide with the anterior margin of the plastron. Posteriorly, however, there is a deep notch between the hypoplastra 50 mm. in depth, which is circular in outline. The entoplastron is roughly hexagonal with an antero-posterior diameter of 160 mm., and a transverse diameter of 195 mm. The carapace as well as the plastron is thin, averaging approximately 10 mm. in thickness, and in many places being not more than 5 mm.

THE CARAPACE

The carapace, as already stated, was mostly missing due to the fact that part of it had been exposed and was very badly weathered. Nevertheless, its general contour could be determined, and it may be said that it was relatively broad and low in comparison to its length. It was highest in the mid-section and sloped gently toward the anterior and more rapidly toward the posterior. The posterior margin projected slightly beyond the limits of the hypoplastra, while in front the epiplastra projected slightly beyond the anterior margin of the carapace.

RELATIONSHIPS

The specimen is closely related to the genus *Testudo* as defined by Hay (1908),[2] but differs from that genus in several important respects: (1) the circular outline of the epiplastron; (2) the broad, short head; (3) the extreme thinness of the carapace and plastron; and (4) the large size of the animal as compared to members of the genus *Testudo*.

The specimen most closely approaches the *Testudo hexagonata* described by Cope (1892)[3] from the Rock Creek beds of Briscoe County, Texas (Lower Pleistocene). In Cope's specimen the epiplastron seems to have been lost, but in the figure it is shown with an outline similar to that of the *Bysmachelys canyonensis*. The skull and other skeletal elements were not found so it is impossible to

[2] O. P. Hay, "The Fossil Turtles of North America," *Publ. Carnegie Inst. Washington* (1908).

[3] E. D. Cope, "The Fauna of the Equus Beds," *4th Ann. Rep. Geol. Surv. Texas* (1892).

make as close a comparison as would be desired. The fact that the entoplastron in the two forms is similar is not thought to be sufficient evidence that they are the same species.

CONCLUSION

It is the author's conclusion, therefore, that the specimen herein described should be placed in a new genus, *Bysmachelys*, so named because of the very broad head (from Greek *bysma*, meaning plug, and *chelone*, tortoise). The species name, *canyonensis*, is for the town of Canyon, Texas, near which it was found.

NEW MARSUPIALS FROM THE TERTIARY OF NEBRASKA

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Walker Museum, University of Chicago

ABSTRACT

The known range of *Peratherium* is extended to the Lower Harrison Miocene by the discovery of *Peratherium youngi*, new species. *Nanodelphys minutus*, new genus and species, is described and placed in the Thlaeodontinae, a subfamily previously known only from the Cretaceous. This newly discovered specimen is from the Brule, Oligocene, and thus greatly extends the known geologic range of the group.

INTRODUCTION

During the summer of 1936, while prospecting for fossil vertebrates in the Harrison beds near Agate, Nebraska, Mr. P. T. Young, accompanied by the writer, found a lens of fine, unconsolidated sand which contains numerous fragments and teeth of small mammals, the most common of which are of heteromyid rodents. Among these fossils was found a single tooth of *Peratherium* which appears to be the first record of a didelphid marsupial in the North American Tertiary in beds of post-Oligocene age. In the Old World *Peratherium* is known in the late Miocene, but hitherto in America the latest record was that of *Peratherium merriami* from the John Day Oligocene of Oregon.[1] *Peratherium* is well represented in the White River of the Great Plains, and forms that are not generically separable are known to occur in the Wasatch and Bridger Eocene.[2] The tooth here considered thus extends the known range of the genus well into Lower Miocene.

Also discussed in the present paper is a new marsupial, which appears to be a thlaeodontine didelphid, from the Brule, Oligocene, near Harrison, Nebraska. Until the present, members of this subfamily have been known only from the Lance Cretaceous and equivalents.

[1] Chester Stock and E. L. Furlong, "A Marsupial from the John Day Oligocene of Logan Butte, Eastern Oregon," *Univ. Calif. Pub. Bull. Dept. Geol. Sci.*, Vol. XIII, No. 8 (1922), pp. 311–17.

[2] G. G. Simpson, "American Eocene Didelphids," *Amer. Mus. Nov.*, No. 307 (1928), pp. 1–7.

DIDELPHIDAE

DIDELPHINAE

PERATHERIUM YOUNGI, NEW SPECIES

Type.—University of Chicago No. 1544. Left M^3 moderately worn. Collected by P. T. Young, 1936.

Horizon and locality.—Lower Harrison beds of the Lower Miocene; about 70 feet below its contact with Upper Harrison. Eight miles east of Agate, Sioux County, Nebraska; 1 mile east of *Stenomylus* quarry.

Diagnosis.—Size of *Peratherium fugax;* protoconule and metaconule absent; stylar cusp *A* absent, *B* not prominent; stylar cusp *C* prominent and situated posterior to tip of the anterior spur of the metacone.

FIG. 1.—*Peratherium youngi*, holotype. External and occlusal views of M^3. × 17.

Discussion.—Of the foregoing characters two seem to represent true advancement over the Oligocene species of *Peratherium:* (1) the loss or great reduction of the conules and (2) the more posterior position of stylar cusp *C*. In M^2 of *Peratherium fugax* the complete series of stylar cusps is present. *A* is small but persists at the tip of the anterior spur of the paracone; *B* is larger and is just posterior to *A; C*, with two accessory cuspules on its anterior slope, is opposite the anterior spur of the metacone; *D*, the prominence of which is variable, is situated on the anterior slope of *E* at the posterior extremity of the tooth.

Stylar cusps *A*, *B*, *D*, and *E* in M^3 of *Peratherium fugax* are of the same relative prominence and position as those of M^2. In M^3, however, *C*, with its accessory cuspules gone, is directly opposite the junction of the median spurs of the paracone and metacone. Examination of a large number of teeth shows this median position of stylar cusp *C* to be constant in M^3 of *Peratherium fugax*. In M^3 of *Peratherium merriami* a similar median position is occupied by this cusp.[3] In M^3 of *Didelphis*, opposite the metacone, is a prominent stylar cusp which is apparently homologous with *C* of *Peratherium*. The position of stylar cusp *C* in *Peratherium youngi* appears to be

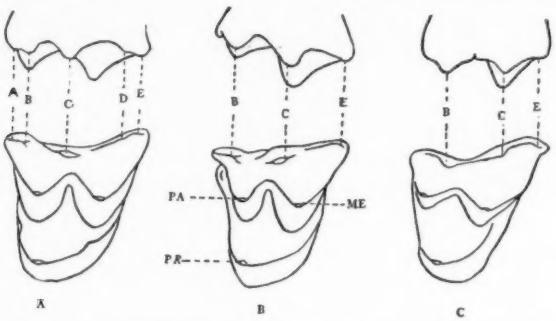

FIG. 2.—External and occlusal views of M^3 of (*A*) *Peratherium fugax*, (*B*) *Peratherium youngi*, and (*C*) *Didelphis*. *A* and *B*, × 11; *C*, × 3½.

intermediate in position between that in *Peratherium fugax* and the recent didelphids. If the homology as indicated is correct, *Peratherium youngi* represents a structural and phylogenetic stage between *Peratherium fugax* and the recent opossums.

The fact that didelphids have been known in the North American Tertiary only from pre-Miocene beds has led to the assumption that they became extinct just prior to Miocene times. Careful examination of the evidence, however, indicates that there is no real reason to assume that the Didelphinae ever became extinct in North America.[4] The life-habits of *Peratherium* and its immediate descendants were doubtless similar to those of *Marmosa* and its kin, which are

[3] Stock and Furlong, *op. cit.*, p. 315.

[4] Simpson, *op. cit.*, p. 2.

forest-living animals nesting in trees.[5] Such habits would not favor skeletal preservation, and it seems remarkable that the fossil record of this conservative group is as complete as it is. In addition to the scarcity of the necessary faunal facies represented in our fossil localities, there is the probability that these forms, unless abundant, would be overlooked because of their small size.

As the oncoming colder climate, which reached its climax in the Pleistocene, affected the fauna, the later Tertiary didelphids were probably forced southward where they gave rise to *Didelphis* and to the *Marmosa* group of Central and South America. From the evidence available it does not appear likely that the opossums could have originated in South America. The known didelphids of the early Tertiary of South America were aberrant to the extent that they are placed in a distinct subfamily by Simpson,[6] the Microbiotherinae. When the land bridge between North and South America was available for migration, or, more probably, when conditions were such that natural raft transportation was possible, the opossums were in a geographic position to occupy readily this newly accessible, favorable habitat across the isthmus. This would account for the sudden appearance of opossums in the "Arancanense" (Lower Pliocene) of South America.[7]

Gazin has suggested an Oligocene or Lower Miocene age for the Florissant beds of Colorado on the basis of the occurrence of *Peratherium* there.[8] Studies of the fish, birds, insects, and plants in the Florissant have led to a variety of opinions concerning its age. Peale regarded the beds as Pliocene; Cope, as Eocene or Miocene; Lesquereux, first as Miocene, later as Oligocene; Scudder, as Oligocene; Cockerell, as Miocene; and Knowlton and Berry, as Miocene. Although the present notice does not offer evidence which will help to date these beds, it does reduce the significance of the occurrence of

[5] G. H. H. Tate, "A Systematic Revision of the Marsupial Genus Marmosa, with a Discussion of the Adaptive Radiation of the Murine Opossums," *Bull. Amer. Mus. Nat. Hist.*, Vol. LXVI (1933), p. 7.

[6] G. G. Simpson, "American Mesozoic Mammalia," *Mem. Peabody Mus.*, Vol. III, Part I (1929), p. 116.

[7] Bryan Patterson, personal communication.

[8] C. L. Gazin, "A Marsupial from the Florissant Beds (Tertiary) of Colorado," *Jour. Paleon.*, Vol. IX, No. 1 (1935), pp. 57–62.

Peratherium, for on the basis of the occurrence of this form the Florissant might be of any age from Eocene to Miocene, with even a greater range probable.

THLAEODONTINAE[9]

NANODELPHYS, NEW GENUS

Genotype.—*Nanodelphys minutus* McGrew.

Diagnosis.—M^2 and M^3 possess the following characters: median stylar cusp absent; stylar cusp *B* prominent; paracone and metacone sub-equal; external shelf bilobate; paracone and metacone in middle of transverse diameter of tooth; size small.

NANODELPHYS MINUTUS, NEW SPECIES

Holotype.—University of Chicago No. 1545; portion of left maxillary with M^2 and M^3 slightly worn. Collected by Mrs. Paul O. McGrew, 1936.

Horizon and Locality.—Ten miles northeast of Harrison, Sioux County, Nebraska. Lower Brule.

Diagnosis.—Anteroposterior diameter of M^{2-3} 2.5 mm.; protoconule and metaconule absent; inner basin narrow anteroposteriorly.

Discussion.—The anterior stylar cusp (*A*) is small and is situated on the anterior slope of *B*. *B* is by far the largest of the stylar cusps and equals the paracone and metacone in height. The median stylar cusp is absent and there is no swelling which might indicate that wear is responsible for its absence. Stylar cusps *D* and *E* are both present, but are small and low. There is a broad outer shelf which is deeply cleft on M^3 and less so on M^2. The paracone and metacone are essentially equal in size and height on M^3. On M^2 the paracone is slightly smaller than the metacone but not sufficiently to be regarded as a reduced cusp. On both M^2 and M^3 a relatively strong crest runs from the paracone to stylar cusp *E*, and a less prominent one from the metacone to the inner slope of stylar cusp *B*.

On the basis of the foregoing characters, which are essentially those of the Thlaeodontinae, *Nanodelphys* must be regarded, for the present, as a member of that subfamily. Unfortunately no premolars were found and it cannot be known whether or not they are

[9] O. P. Hay, *Second Bibliography and Catalogue of the Fossil Vertebrata of North America*, Vol. II (1930), p. 390; G. G. Simpson, "Notes on the Classification of Recent and Fossil Opossums," *Jour. Mammalogy*, Vol. XVI, No. 2 (1935), pp. 134–37.

bulbous as are those of the Lance Thlaeodontines. Since this is one of the most peculiar characteristics of the Lance genera, the present specimen might be considered as insufficient evidence for its inclusion within a group so far removed geologically, but its probable

FIG. 3.—*Nanodelphys minutus*, genoholotype. External and occlusal views of M^2 and M^3. × 19.

life-habits and its small size could explain its apparent absence from other fossil localities. In all probability future work will definitely prove the relationship.

Nanodelphys differs from certain similar didelphid genera as follows.

Didelphodon, Lance, Wyoming: *Nanodelphys* is apparently more closely related to this genus than to the other known thlaeodontines, and upon the basis of its characters could be a direct descendant. The presence of spurs on the paracone and metacone of *Nanodelphys* may be regarded as a progressive character which, even in such a conservative group, could become apparent after the lapse of time

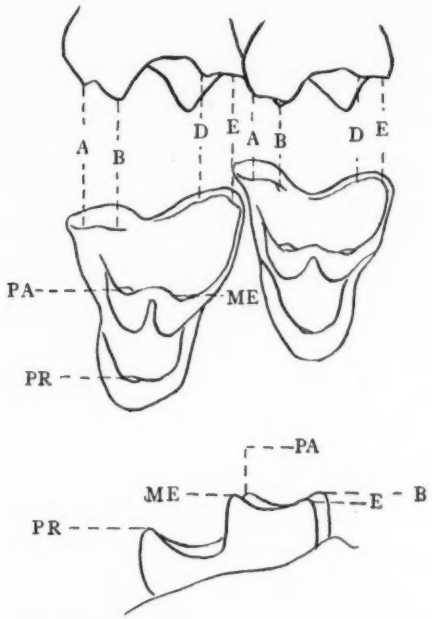

FIG. 4.—*Nanodelphys minutus*, genoholotype. External and occlusal views of M^2 and M^3; posterior view of M^3. × 20.

between Lance and Brule. The small size of *Nanodelphys* is probably of no significance since great size variation is common within a subfamily, i.e., *Marmosa* and *Didelphis*. The stylar cusps of *Nanodelphys* and *Didelphodon* are similar in arrangement and relative prominence. The Lance genus has reduced conules which are absent in *Nanodelphys*, but this again may be regarded as a progressive trend paralleling that seen in the Didelphinae. The bilobate external shelf is similar in both genera.

Thlaeodon, Lance, South Dakota: The upper molars of *Thlaeodon* are too poorly known to permit satisfactory comparison. M^1 of *Thlaeodon* has a less pronounced external median cleft than do M^2 and M^3 of *Nanodelphys* and the stylar cusps are in different relative positions.

Ectoconodon, Lance, Wyoming and Montana: *Nanodelphys* lacks the median stylar cusp and the conules that are present in *Ectoconodon* and has a greater transverse width in proportion to its anteroposterior length than does *Ectoconodon*.

Alphadon, Lance, Wyoming: In size *Alphadon* is close to *Nanodelphys*, but the presence of the median stylar cusp of *Alphadon* makes any close relationship improbable. In other molar characters, however, the two genera are quite similar.

From the single specimen of *Nanodelphys* the genus seems to represent an Oligocene survivor of a primitive, unsuccessful group of marsupials which enjoyed considerable expansion in the late Cretaceous of North America, but which, as a whole, was unable to withstand the competition of the adaptive placentals of the early Tertiary.

REVIEWS

Wissenschaftliche Ergebnisse der deutschen atlantischen Expedition auf dem Forschungs- und Vermessungschiff "Meteor" 1925–1927. Vol. III, Part II, sec. 1; Part III, secs. 1 and 2. Berlin and Leipzig: Verlag von Walter de Gruyter & Co. Figs. 11; pls. 2— figs. 107; pls. 4; profiles 3.

Part II of Volume III is by O. Pratje and concerns the collection and analysis of the sediments of the South Atlantic Ocean. An index map shows the route of the vessel and the locations of the samples collected for both the southern and the equatorial sets of sediments. A description is given of the equipment used on the vessel, and especial attention is paid to the Lucas sounding machine which is described in detail both in the text and in the accompanying figures. For sample-collecting a sampling tube of the general Ekmann pattern, but with modifications, was used. Supplementary sampling devices included grab buckets. A detailed analysis was made of the entire process of sample-collecting with the sounding machine in terms of the time required, the frictional effects, angle of withdrawal, and the like. The discussion will prove of practical value in the organization of similar expeditions.

The remainder of Pratje's report includes a detailed discussion of the preparation of the samples for analysis and of the methods used for mechanical analysis. The Atterberg cylinder and Kopecky's elutriator were used for the latter. Methods of chemical analysis, especially for the determination of carbonates, complete the text discussion. At the end of the section is a tabular list of the samples collected on the expedition, showing location, depth, and remarks concerning the nature of the deposits.

The first and second sections of Part III include the reports of C. W. Correns and of W. Schott. Correns' reports are in several sections, the first of which concerns briefly the sampling methods and in greater detail the methods of preparing the sediments for analysis, as well as the methods of mechanical analysis, chemical analysis, and X-ray analysis. Comparisons were made of several methods of mechanical analysis and of the influence of various dispersion procedures on the results. For the final analyses the Atterberg cylinder and Oden's sedimentation balance were used. The chemical analyses include methods for determining or-

ganic content, and Fe, Ti, Mn, and P. X-ray data were obtained on the finer mineral fractions of the samples.

The second portion of Correns' report includes, first, a tabular summary of all the analytical data obtained. Each core sample was divided into an upper and a lower portion, which were separately analyzed for comparative data. The data include the mechanical analysis by grades, the organic content, the Fe, Mn, Ti, and P content, and X-ray data on the results of the analysis, both theoretical and practical, with numerous maps showing the areal variation of the several characteristics studied. Among these maps is an interesting one which shows the areal distribution of the clay minerals, based on X-ray data. The minerals found include kaolinite, halloysite, and montmorillonite. The map shows a predominance of kaolinite on the sea bottom, with montmorillonite in only a few scattered localities, apparently related to regions of basaltic volcanism.

In a summary at the end of his reports Correns discusses the nature of the bottom deposits. It appears that earlier distinctions between deep-sea deposits were largely artificial, inasmuch as a continuous gradation was found from one to the other. That is, the deep-sea sediments show a gradation from blue muds, with their rapid settling of mineral fragments, through carbonate-rich clays and Globigerina ooze to red muds, in which the finest mineral grains slowly settled and from which the carbonate material was redissolved. All the samples showed appreciable amounts of terrigenous material in the mineral portions, carried in by wind or currents. Volcanic material was most pronounced in the vicinity of volcanic regions. Important components of the sediments were the new minerals formed, such as iron and manganese compounds, glauconite, and pyrite. The carbonate content of the deep-sea sediments was entirely of organic origin, and locally it is redissolved by the sea water.

The second portion of Part III is by W. Schott and concerns the foraminifera of the equatorial Atlantic. The samples were examined section by section, so that the distribution of species through each sample was examined in some detail. Maps were prepared of the areal distribution of many of the forms. The distribution of faunas in the core samples showed three divisions. The upper portion, with *Globorotalia menardii*, was deposited since the end of the last glaciation. Below this is a thicker layer free from *Globorotalia*, presumably deposited during the glaciation, and in the lower portion another zone of *G. menardii*, deposited during an interglacial interval. From these data Schott concludes that sedimentation during the glacial period was much more pronounced than since that period.

The entire report is well organized and clearly written. Pratje's report will be particularly interesting for its practical discussion of the equipment used, Correns' reports afford a wealth of new data of interest to sedimentary petrologists and oceanographers, and Schott's report will stimulate the interest of micro-paleontologists. The volume is clearly printed and the figures and plates well reproduced. The report belongs in every geological library and unquestionably will be much referred to for the wealth of reliable data included.

W. C. KRUMBEIN

Down to Earth. By CAREY CRONEIS and W. C. KRUMBEIN. Chicago: University of Chicago Press, 1936. Pp. 501+xviii; numerous figures; pls. 64. $3.75.

These relatively young authors have written a book which is amazing to this reviewer. Teachers of brief cultural survey courses, whether they like it well enough to adopt it as a text or not, will find it interesting and worthy of serious consideration. Nowhere does this reviewer know of a book better adapted to the use of the lay reader who wants the geological story written in a nontechnical, nonprofessional manner.

In the preparation of the book every attempt was made to get away from conventional forms. It does not look much like a textbook. It is written in an easy conversational style, which in places is almost playful. The broad facts, principles, theories, and methods of the science are clearly presented and to a surprising degree of completeness in spite of a considerable amount of repetition involved in numerous forward and backward references. Technical and professional terms are reduced to a minimum. Only enough detail is introduced to support and clarify the generalizations. A large number of excellent photographic illustrations are inserted in three groups of plates.

Although both the physical and the historical aspects of the subject are covered, the book is not divided into Parts I and II, and it is not evident where physical geology ends and historical geology begins. There are no center or side headings within the chapters. Many words, phrases, or whole sentences are printed in bold-face type or in italics for emphasis, however. The figures throughout the text are not numbered.

With its fifty-one chapters averaging about ten pages each, the book may be long enough for the twenty- or thirty-geology-lectures course at Chicago, for which it was designed especially, but hardly for the more common fifty- or sixty-lectures survey course elsewhere. Perhaps it is intended more for general reading to supplement a series of lectures than for use as a textbook in which specific assignments are made.

As is probably to be expected in a work of this sort, the discerning student or his teacher will find numerous inconsistencies and inaccuracies. On page 14 one reads: ". . . . nor were any of the rocks now exposed on the earth ever more than a relatively few miles below the surface," and on page 17: "Now it happens that many rocks are formed deep beneath the surface of the earth. . . . ." On page 14 the lithosphere, atmosphere, and hydrosphere are said to comprise the earth, and on page 27 the biosphere is added. On page 19 a mineral is defined as ". . . . a naturally occurring chemical compound. . . . ." This would exclude the minerals that are elements and would include gaseous and liquid water, gaseous carbon dioxide, the salts dissolved in the sea, such as calcium bicarbonate, and the cellulose of organisms. As rocks consist of minerals, it could properly be inferred from this definition that the hydrosphere, the atmosphere, and even the biosphere are rocks and belong in the lithosphere. On page 325 one reads: "The Ordovician period is notable for its great inundations, the largest of which literally had the North American continent awash from stem to stern," and wonders as to the source of the abundant sediments of that time. Surely a part of the goal of courses in geology is to encourage and train students to draw logical conclusions from stated facts. Such loose statements as these do more harm than good in attempts to reach this particular goal.

It is implied that individual reptiles, mammals, and even ground water schemed things out, consciously struggled upward, and had other human attributes. Early Mesozoic reptiles "had already started to explore the possibility of radiation into more exciting habitats," but their "more venturesome cousins, however, moved back into the sea or invaded the air" (p. 401). Reptiles "looked fondly toward the air" (p. 403). "Either the bad example which the dinosaurs had set or their new-found freedom was too much for them [the mammals]" (p. 449). On page 80 certain factors are said to ". . . . decide whether ground water is to be in a dissolving or depositing mood." Such statements tend to give students erroneous ideas of earth history and, in fact, border on "nature faking."

In some ways, at least, the book is not well organized. In spite of the true statement in bold-face type on page 428 that "there is no deposition without attendant erosion," the erosional and depositional aspects of the work of such agents as streams, wind, and glaciers are separated into different chapters. Wind erosion and a part of stream erosion are given in chapter vi, "Winds and Turbulent Motion"; more of stream erosion in chapter vii, "Valleys and Streams," and in chapter viii, "The Everlasting Hills"; and glacial erosion in chapter x, "Rivers of Ice"; but deposition by all three of these agents is discussed in chapter xi, "End of

the Line." Then chapter xiii, "Plus and Minus," repeats considerably and reviews alluvial fans, natural levees, deltas, stream erosion, dunes, beaches, and moraines. On the other hand, both solution and deposition by ground water are given together in chapter ix, "Underground Water and Laminar Flow," and both erosion and deposition on shore lines in chapter xii, "The Bounding Main." Are waves and their accompanying currents less turbulent than winds, streams, and glaciers, so that there is a closer connection between sea cliffs and spits than between blowholes and sand dunes, or between valleys and natural levees, or between ice-gouged basins and glacial moraines?

Chapter xxix, "Mountains and Climates," is not unified. Volcanism and igneous rocks, which are certainly closely related, are widely separated. The geology of oil and gas, which properly belongs under Ordovician economic products on page 331 where oil and gas are first mentioned, is treated at length on pages 472–76 in chapter l, "Money and Politics."

A. C. TROWBRIDGE

Type Invertebrate Fossils of North America (Devonian), Unit 7b, Ammonoidea. By A. K. MILLER. Philadelphia: Wagner Free Institute of Science, 1936. 50 cards. $8\frac{1}{2} \times 11$ in. $2.50.

This is the first unit of the card catalogue of the invertebrate fossils of North America which is being prepared under the sponsorship of the Paleontological Society. Some vague idea of the enormity of this project may be gained from the fact that this initial publication, which required months of research and involved visits to many museums, will constitute a mere 0.1 of 1 per cent of the entire catalogue, if and when it is ever completed. Nevertheless, the first fifty cards are extremely valuable for a number of reasons.

They give definite indication that the entire program is a logical and feasible one despite the enormous amount of work which will be involved in its completion. The printing of the original figures, together with the original or revised descriptions, occurrences, and observations, on single sheets of good-grade paper of letter size has turned out to be more successful than might have been anticipated. The cards are easy to handle and, of course, fit readily into the standard letter file. This portion of the catalogue is also valuable in its own right, not alone because the material presented is intrinsically important but because the author has set a high standard of excellence for the other catalogue compilers to emulate. Furthermore, it must be insisted that, if the subsequent

portions of the catalogue are issued in conformity with the present one, they will not be compilations in the ordinary somewhat derogatory sense; for in the preparation of the material contained in this section a great deal of new material has been added. The type specimens have all been restudied, and in some cases new photographs or new illustrations have been prepared.

Four specimens of North American Devonian ammonoids are not included in this unit since they belong to unnamed genera which Professor Miller is describing in a monograph of the Devonian ammonoids of America which is now in press. Cards of these new species, as well as for the others which doubtlessly will be described later, are eventually to be added to the present set. Thus the flexibility of the card system is brought into use, and the workers will have available at all times an up-to-date reference to this as well as to the other classes to be catalogued later.

Criticisms of such a pioneering effort may seem invidious. The results, however, might have been slightly improved had a standard method of presentation been followed on all, rather than on most, cards; and the scheme of labeling each of the present species Ammonoidea 1, 2, 3, etc., does not permit the introduction of description of new species without some adjustment in numbering. Had the numbers been omitted, the alphabetical sequence followed in this first group of cards could have been maintained indefinitely.

CAREY CRONEIS

Geology and Mineral Deposits of the Bay of Exploits Area. By GEORGE R. HEYL. ("Newfoundland Department of Natural Resources, Geological Section," Bull. No. 3.) St. John's, 1936. Pp. 66; figs. 8; pls. 7; tables 9.

Geology of the Southern Half of the Bay of Islands Igneous Complex. By JOHN R. COOPER. ("Newfoundland Department of Natural Resources, Geological Section," Bull. No. 4.) St. John's, 1936. Pp. 62; figs. 14; pls. 7.

Princeton University and the Newfoundland government, through the Geological Section of its Department of Natural Resources, are jointly responsible in large measure for the addition of two new separate bulletins to the literature on the geology of Newfoundland. Bulletin No. 3 is the result of Princeton University geological expeditions to Newfoundland under the leadership of Dr. A. K. Snelgrove, Newfoundland government geologist. Bulletin No. 4 is based on a doctorate dissertation

sponsored by Princeton. Assays, drafting, mapping, etc., in both studies are the work of the staff of the Newfoundland Department of Natural Resources.

In the Bay of Exploits area (Bull. No. 3), there outcrop Ordovician and Silurian sedimentary and igneous extrusive rocks, folded, faulted, and intruded at least once subsequently. The question of a Silurian or Devonian age for the orogeny and batholithic emplacement is discussed, and in this connection the comparable history of this region with the west coast of Europe rather than with the rest of the east coast of America is noted. The method of emplacement of the batholith is considered and field evidence adduced for upward and sideward thrust with a small amount of stoping. Stibnite, arsenopyrite, gold-arsenopyrite, bismuthinite, tetrahedrite, chalcocite, and pyrhotite are the ore minerals which are genetically related to the granodiorite batholith. The only others found in the area are sedimentary hematite and manganese oxides and chalcopyrite, related to a diorite intrusion.

Bulletin No. 4—on the southern half of the Bay of Islands igneous complex—is ". . . . primarily a petrological and structural study of a portion of the western serpentine belt of Newfoundland." The complex is interpreted as a single lopolithic sheet. A very marked pseudo-stratification shows interesting similarities and differences when compared with both the Bushveld and the Duluth types of lopolith. The Bay of Islands complex may, according to Cooper, be considered as a connecting link between the more typical lopoliths and the "ultramafic rocks long recognized as characteristic of geosynclines." The petrography and petrographic sequences of the lopolith are worked out in great detail; petrogenetic deductions are correspondingly specific. A short description of the economic geology of the complex shows chromite, asbestos, copper, and nickel.

JEAN CAMPBELL GRACE

Erläuterung zur geologisch-morphologischen Übersichtskarte des norddeutschen Vereisungsgebietes ("Explanation To Accompany the Geomorphic Reconnaissance Map of the Glaciated Part of Northern Germany"). By P. WOLDSTEDT. Berlin: Preussische Geologische Landesanstalt, 1935. Pp. 33; with accompanying map.

This explanation accompanies a map drawn on a scale of 1:1,500,000. The mapped area extends from the Baltic coast to 51° N. lat. and from Amsterdam east to 23° E. long. (about 100 kilometers east of Warsaw).

The map shows the principal terminal moraines, the ground morainic areas, loess regions, and the like. It demonstrates excellently the great continuous late-glacial morainic belts and outwash, extending from the Kiel Canal to East Prussia; the effect of the higher topography, from the Hartz to Kraków, in stopping the ice and harboring the loess deposits of central Germany; the role of the late moraines in forming the Isthmus of Schleswig; and the topographic control exercised by the large moraines upon the lower courses of such streams as the Weser, Elbe, and Oder.

The brief text that accompanies this interesting map is especially noteworthy. It introduces much new material, especially contributions by such scholars as Grahmann, Wahnschaffe, and Schucht. The text begins with an explanation of terms. Of interest, in reflecting the European viewpoint, is the emphasis on the relationship between kames and eskers (Ger. *Oser*). Outwash plains are designated *Sander* and, as with the *Oser*, their original topography is unusually well preserved, even in so moist a climate, because their high porosity reduces the runoff.

As to areal relations, melt-waters, both from the ice sheets and from the Alpine glaciers to the south, ran generally northwestward down the courses of the larger streams, and so to the sea; in some of these basins are varved deposits resulting from local ponding of such channels. There is no positive evidence of the first or earliest glacial stage in north Germany, though traces are believed to have been recognized in Holland and in Poland (Jaroslavian and Sandomirian); these are probably the equivalent of the Günz of Alpine geologists. Three other stages, with corresponding interstages, are definitely recognized and mapped, however; these are designated the Elster, Saale, and Weichsel, respectively, in place of the older Alpine names. Beneath them all are the Tegeler clays, which bear a warm-climate fauna. The Elster glaciation was followed by subsidence and marine invasion. Then came the Saale and in turn the Weichsel stage, which dominates the present topography and strongly suggests, in its reduced extent but more marked features, the late Wisconsin stage of North America. At the same time small valley glaciers flowed northward from the Hartz Mountains and the Riesengebirge.

Physiographic features of the later age are the large dunes of the coast in the northeast (described as dominantly crescentic in form) and a set of terraces extending across the entire middle section of the country. The text ends with a catalogue and locality list of prehistoric human remains and artifacts.

All in all, this is an interesting collection of facts, ably assembled and especially useful to the American geologist who desires a generalized

picture of the Pleistocene in northern Europe and an acquaintance with the progress made by German physiographers in the last twenty-five years.

CHARLES H. BEHRE, JR.

The Geology of the Minneapolis–St. Paul Metropolitan Area. By GEORGE M. SCHWARTZ. *Minnesota Geological Survey Bulletin 27.* Minneapolis: University of Minnesota Press, 1936. Pp. 267; figs. 45; pls. 7. $3.50.

A work of primarily local interest and one which emphasizes the practical aspects of a detailed geologic and geographic study of a small area of economic rather than physical boundaries, this report answers for the Twin Cities of Minnesota a demand which is gradually being met in many of the urban centers of the United States.

The bedrock of the region under consideration, which includes all of Ramsey and Hennepin, most of Washington, and parts of Dakota, Anoka, Scott, and Carver counties, consists of Cambrian and Ordovician sediments. Four drift sheets, or remnants of them, lie at or near the surface of the district.

Many detailed stratigraphic sections and descriptions of glacial deposits, with a brief history of the area and a more elaborate one of the changes in drainage effected by the glaciers, make up the longest chapter of the book. Short chapters deal with the relatively simple geologic structure and the geography and vegetation of the area. The long chapter on the economic geology treats mainly of water supply and building-foundation conditions. Brief estimates of stone, clay, peat, and marl resources are given.

Nearly half the book is devoted to tabulations of underground data, including 796 well logs and some borings along the Mississippi River. The seven plates consist of a geologic map of the area, superposed on a cultural pattern (scale: 1 in. equals 8,000 ft.), two series of cross sections, two structural contour maps, one artesian diagram, and one map of glacial deposits.

JEAN GRACE